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Life-Cycle Cost Analysis for Protection and Rehabilitation of Concrete Bridges Relative to Reinforcement Corrosion

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Foreword

This report consists of three parts. Part One discusses the development of a systematic methodology to determine the most cost-effective treatment, and its timing, for specific concrete bridge components that are deteriorating or are subject to deterioration. Part Two presents the methodology in the form of a handbook for highway agencies. The handbook includes nomograms, tables and other aids to facilitate the selection of the most cost-effective strategy. The methodology has also been incorporated into a microcomputer program. Part Three of this report documents the microcomputer program's user's manual, explaining the system's features, options, and displays.

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Abstract

A systematic methodology is presented for highway agencies to use at the project level to determine the most cost-effective treatment, and its timing, for specific concrete bridge components that are deteriorating or are subject to deterioration. The methodology is set forth in the form of both a handbook and a computer program. The methodology in its present form applies only when the predominant concrete deterioration is associated with chloride-induced corrosion of the reinforcing steel. The methodology is designed to be flexible and can be tailored to suit the needs of individual highway agencies.

Executive Summary

The deterioration of concrete bridges is a major problem in the operation of the nation's highway system. The cost of repairing or replacing deteriorating bridges is one of the most expensive items faced by highway agencies, and it is increasing rapidly. The main cause of the deterioration is the use of salt in winter maintenance operations. The salt penetrates the concrete and corrodes the reinforcing steel, eventually resulting in internal cracking and surface spalling of the concrete. The deterioration occurs on all concrete bridge components, including decks, superstructure elements, and substructure elements. Similar corrosion-induced deterioration also occurs on concrete components exposed to marine environments.

In order to reduce the cost of bridge maintenance at the network level, it is essential that rational actions are taken at the project level. This report provides a systematic methodology to guide technical personnel of highway agencies to rational decisions regarding treatment of specific concrete bridge components. The methodology applies the concept of life-cycle cost. The output from the methodology answers the user's questions regarding the type and timing of treatment to achieve the lowest life-cycle cost. The methodology is set forth in the form of both a handbook and a computer program.

The methodology takes the following factors into account to conduct life-cycle cost analysis:

1- The condition of the concrete component and its performance.

2- The technical compatibility, cost, and service life of the range of treatment alternatives from which the selection can be made.

The methodology recommends which site-specific condition data to obtain and how to use the data to quantify the concrete condition in terms of an index. The methodology also provides the user with the performance curve predicting the condition index of the component in the future, based on the available condition data. From the performance

curve, the user will determine the time to maximum tolerable condition index. The time of maximum tolerable condition is not necessarily the optimum time to treat the concrete. The rest of the methodology is used to determine the type of treatment and its timing to achieve the lowest life-cycle cost.

The methodology presents a range of potential alternatives to treat the concrete and helps the user screen out the alternatives that are not technically compatible with the component. The methodology then shows the user how to estimate costs involved in applying each appropriate type of treatment. Both agency and user costs can be included.

Since the methodology applies the life-cycle cost concept, the performance of concrete after the treatment also needs to be predicted. The methodology utilizes the concept of "trend in the rate of corrosion after the treatment" to predict the performance after the treatment. Each potential treatment alternative is represented by a certain trend in the rate of corrosion of reinforcing steel after the treatment. The user, however, has the option of changing the trend in the rate of corrosion that is assigned to a given treatment, based on the agency's experience with that particular treatment. Unlike the trend in the rate of corrosion, the actual rate of corrosion value generally does not play a role in the methodology and it is only needed when certain concrete conditions are present. However, since historical rate of corrosion data are limited at this time, the availability of further rate of corrosion data can support the rate of corrosion trends assigned to various treatments in the methodology. Therefore, agencies are encouraged to collect pre- and post-treatment rate of corrosion data from selected sites.

To conduct life-cycle cost analysis, the user of the methodology will first select a type of treatment from the range of compatible treatment alternatives available. The user will then consider treating the concrete component at different points in time for life-cycle cost comparison. Those different points in time are bounded by (1) the present time, (2) the time of maximum tolerable condition. The economic analysis of each of the strategies considered is done systematically. All costs associated with each strategy, including costs of repeated cycles of treatment (agency and user costs) are then input into the system. The output from the system is the life-cycle cost of each strategy. The lowest life-cycle cost represents the optimum strategy (i.e., optimum time of treatment) for the type of treatment selected.

Once the optimum time of treatment and life-cycle cost for one treatment is determined, the user will employ the same procedure to determine the optimum time of treatment and life-cycle cost for other treatments. At the end, the user will be able to prioritize the various types of treatments based on their life-cycle costs. The most cost-effective treatment will be the one with the lowest life-cycle cost, and it should be applied at its optimum time.

Glossary of Variables

a	Percent of free-flow travel time across bridge, representing increment in travel time when deck condition is maximum tolerable.
A	Constant controlling rate of deterioration in concrete performance equation.
B	Constant controlling rate of deterioration in concrete performance equation.
C	Two-way capacity of bridge during normal periods, vehicles per day.
C1	Two-way capacity of bridge during construction, vehicles per day.
CL	Percent of concrete samples with bar-level chlorides higher than corrosion threshold value.
C_o	Number of cement sacks per cubic yard of concrete.
C_m	Rate of corrosion of reinforcing steel when concrete condition is maximum tolerable.
C_p	Rate of corrosion of reinforcing steel measured at present, corresponding to 90th percentile value (average rate of corrosion plus 1.282 standard deviation).
C_r	Rate of corrosion of reinforcing steel at previous repair, rehabilitation, and/or protection.
C^*	Rate of corrosion of reinforcing steel at the time of planned treatment.

COST	Cost of last cycle of treatment in planning horizon.
d	Depth of bar cover corresponding to 10th percentile value (average depth minus 1.282 standard deviation).
d_o	The present worth factor.
D	Total deck area, square feet.
DELAM	Percent of concrete area that is delaminated (not including spalls).
DF	Discount factor.
DF_{20}	Discount factor corresponding to Year 20 in planning horizon.
EI	Effective interest rate.
ESL	Effective service life of treated concrete.
J	The total discounted life-cycle cost to be minimized for a given treatment strategy.
K	The ratio of the slope of corrosion rate line after treatment to the slope of corrosion rate line before treatment.
K_o	Chloride concentration of water, parts per million.
K_1	Value of bridge user time while traveling, dollars per minute per vehicle.
K_2	A calibrating constant for user cost prior to treatment, dollars per vehicle.
l	The life of each treatment following the initial treatment.
m	Periodic maintenance cost, only cathodic protection.
M	A fixed time as for mobilization.
n	Number of each consecutive year in planning horizon.
n_o	An exponent controlling the growth of user cost with deteriorating deck condition.

N	A constant representing the ratio of delaminated concrete areas to spalled concrete areas in a typical case.
P	Concrete water-cement ratio.
P_r	Productivity of treatment, square feet per day.
q_o	Average two-way daily traffic volume across the bridge, vehicles per day.
r	Discount factor for optimization procedure.
R_t	Age of concrete at time to first sign of corrosion-induced deterioration (original version of t_d).
RS	Remaining effective service life of treated concrete beyond the planning horizon.
S	Concrete condition index.
Si	Depth of steel below concrete surface.
S_m	Maximum tolerable concrete condition index.
S_p	Concrete condition index at present.
S_r	Concrete condition index at time of previous repair, rehabilitation, and/or protection.
S_t	Concrete condition index predicted for concrete age of t.
S_{45}	Concrete condition index of 45.
S(t*)	Percent of deck area that is distressed at the time of treatment.
SLVG	Salvage value, present worth.
SPALL	Percent of concrete area that is spalled.
t	Time since initial construction of concrete (age of concrete), years.
t_c	Duration of concrete treatment, days.

t_d	Age of concrete at time to first signs of corrosion-induced deterioration, years.
t_f	Free-flow travel time across the bridge, minutes.
t_m	Age of concrete at the time of maximum tolerable concrete condition, years.
t_o	Age of concrete at time to first sign of corrosion, years.
t_p	Age of concrete at present time, years.
t_r	Age of concrete at the time of previous repair, rehabilitation, and/or protection.
t_t	Increment in travel time across the bridge (or detour around the bridge) caused by construction, minutes.
t^*	Age of concrete at the time of planned treatment, years.
t_{45}	Age of concrete at the time of condition index of 45, years.
U	Incremental increase in user cost due to worsening deck condition, dollars per vehcile.
U_1	User cost during the treatment period, dollars.
U_2	User cost due to worsening deck condition, dollars per year.
W_m	Mixing water in percent of concrete volume.
Z_t	Concrete surface chloride content corresponding to 90th percentile value (average chloride content plus 1.282 standard deviation), percent of concrete weight.
Z_R	Concrete surface chloride content at time to deterioration, percent of concrete weight.
α	A constant used in congestion cost formula.
β	An exponent used in congestion cost formula.

PART I—METHODOLOGY

1. Overview

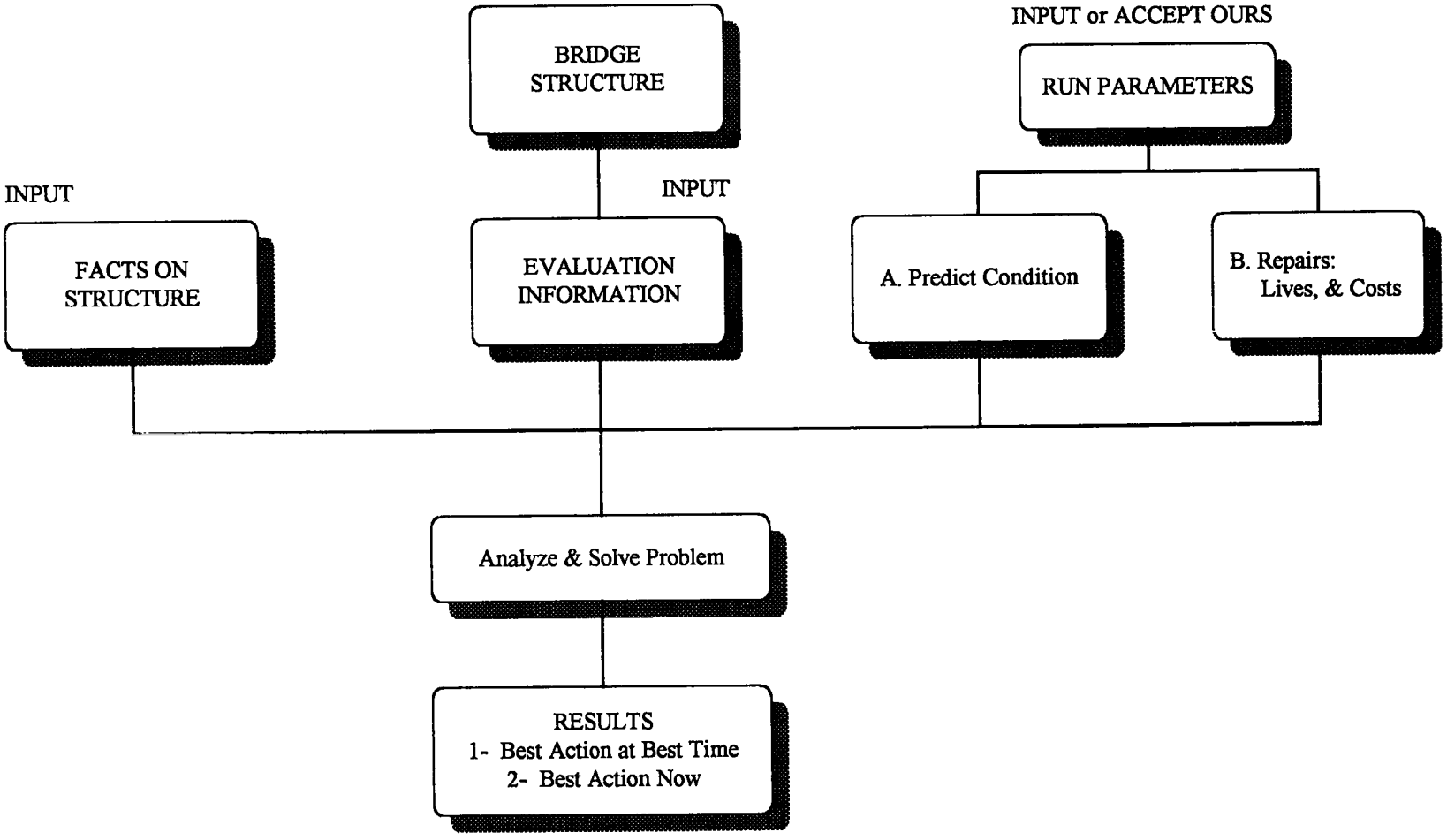
The deterioration of concrete bridges is a major problem in the operation of the nation's highway system. The cost of repairing or replacing deteriorating bridges is one of the most expensive items faced by highway agencies, and it is increasing rapidly. The main cause of the deterioration is the use of salt in winter maintenance operations. The salt penetrates the concrete and corrodes the reinforcing steel, eventually resulting in internal cracking and surface spalling of the concrete. The deterioration occurs on all concrete bridge components, including decks, superstructure elements, and substructure elements. Similar corrosion-induced deterioration also occurs on concrete components exposed to marine environments.

In order to reduce the cost of bridge maintenance at the network level, rational actions are required at the project level on the basis of life-cycle costs. This report discusses a methodology that provides systematic procedures to allow valid life-cycle cost comparison of the available options for protecting and rehabilitating specific concrete bridge components. These procedures are set forth in the form of both a handbook and a computer program. The handbook is contained in Part II of this document; the computer program user's manual, in Part III.

Figure 1 summarizes the general approach of the methodology. Generally, the methodology involves the following objectives:

- Obtain general information on the component, and determine the present condition of the component.
- Quantify concrete condition in terms of an index.
- Predict future condition index.
- Estimate cost of treatment, and determine treatment's maximum possible service life on the basis of non-corrosion-related distress.

Figure 1. General Approach



- Predict concrete condition index after treatment.
- Conduct life-cycle cost analysis to determine the optimum treatment and its timing.

To accomplish those objectives, the methodology is aimed at the following technical goals.

1.1 Technical Goal One: Condition Index Versus Time

Technical Goal One quantifies the present condition of the concrete in terms of an index. Also, it predicts the condition index at any time in the future. To do so, it supplies two appropriate data points on the plot of condition index versus time, so that the concrete performance curve can be determined prior to any treatment. The performance curve is determined for all possible cases (i.e., for concrete members which were built with and without protective systems at the time of the initial construction; for previously rehabilitated members as well as members which have never been rehabilitated; for members presently showing physical distress; and for members which are not yet salt contaminated or distressed).

1.2 Technical Goal Two: Decomposing Condition Index

Technical Goal Two involves devising a means of decomposing the predicted concrete condition index into its distress component parts for the purpose of estimating the physical distress in the concrete in the future, so that treatment cost estimates can be performed.

1.3 Technical Goal Three: Cost and Maximum Service Life of Treatment

Technical Goal Three provides cost and service life information (maximum possible life based on non-corrosion-related distress) for alternative procedures for treatment of concrete.

1.4 Technical Goal Four: Condition Index Versus Time after Treatment

Technical Goal Four supplies procedures to predict the condition index with time after each applicable treatment.

1.5 Technical Goal Five: Life-Cycle Cost Analysis

Technical Goal Five provides procedures to determine the treatment that results in the lowest life-cycle cost, as well as the optimum time to apply that treatment.

1.6 Report Format

This report discusses the technical goals of the methodology. Flowcharts of various modules, questions to the user, and decisions are included in Appendix A. They are helpful in understanding the discussion. Although the technical basis and details are voluminous, the user will see only a short series of questions and then the findings. A sample computer run is demonstrated for Technical Goal One, Condition Index Versus Time, in Appendix B. This computer run is not related to the CORRODE system described in Part III of this document.

2. Technical Goal One

Condition Index Versus Time

2.1 Condition Index

The first step is to quantify the concrete condition. Current research on this and other SHRP research projects suggests that three quantities are indicators of current concrete condition as affected by corrosion:

1. Percent of bar-level concrete samples with chloride content higher than the corrosion threshold value (CL).

2. Percent of concrete area that is delaminated (DELAM), not including spalls.

3. Percent of concrete area that is spalled (SPALL).

Of these, when considering treatment options at a given time, spalling is the most important factor, delamination is second in importance, and chloride contamination at the level of reinforcing steel is the third most important. For the purposes of this project, the relative importance of each of these three factors (as an indicator of the need of treatment) is expressed by assigning the following weights:

> Spalling is three times more important than delamination, while delamination is 2.5 times more important than bar-level chloride contamination.

The condition index (S) may then be quantified at the time of condition survey and on the basis of condition data as follows:

$$S = [CL + 2.5\ (DELAM) + 7.5\ (SPALL)] / 8.5 \qquad \text{(Eq. 2.1)}$$

Appendix C shows in detail how the condition index is calculated. As the concrete gradually deteriorates, its condition index increases. The condition index has a

mathematical maximum of 100 and a minimum of 0, although practically speaking, it is believed that the condition index should not be allowed to exceed 45.

2.2 Prediction of Future Condition Index

Corrosion-induced deterioration in concrete is typically represented in the literature as a piecewise linear function, as shown in Figure 2a. This curve itself is an approximation of how deterioration actually progresses in the field. However, the three linear segments (i.e., the regime of zero damage prior to corrosion initiation at t_o; the intervening period up to the time to deterioration at t_d; and the growth of damage thereafter) cannot conveniently be represented by a single equation. The deterioration model (Condition Index) assumed in this study is therefore shown in Figure 2b. This S-shaped, or logistic, curve is a plot of the following equation.

$$S_t = 100 / [1 + A \exp(-Bt)] \qquad \text{(Eq. 2.2)}$$

where

S_t = concrete condition index predicted for concrete age of t

A,B = parameters controlling the rate of deterioration and the shape of the curve

t = time since initial construction (age of concrete), years

An example of the condition index versus time curve is shown in Figure 3. The two unknown parameters of A and B in the equation are found based on the site-specific data. To find the parameters, two appropriate data points are required. Each data point represents the condition index and the corresponding concrete age. Because of the widely varying members, and their past, present, and future conditions, the two needed data points on the condition index versus time curve cannot always be at the same condition or age. When possible, one of the points will be the age of concrete at the initiation of deterioration (t_d) with an assigned condition index (S_d), and the other will be the age of concrete at the present (t_p) with the condition index at the present (S_p).

As discussed previously, the two terms representing the age of concrete at the initiation of corrosion and the start of physical distress are t_o and t_d, respectively. For the purposes of this effort, the following condition indices were assigned to those items on the basis of experience:

1. Condition index at t_o (S_o): 10 percent chloride contamination, 0 percent delamination, and 0 percent spalling. Therefore, S_o = 1.2.

Figure 2. Bridge Deck Deterioration Model

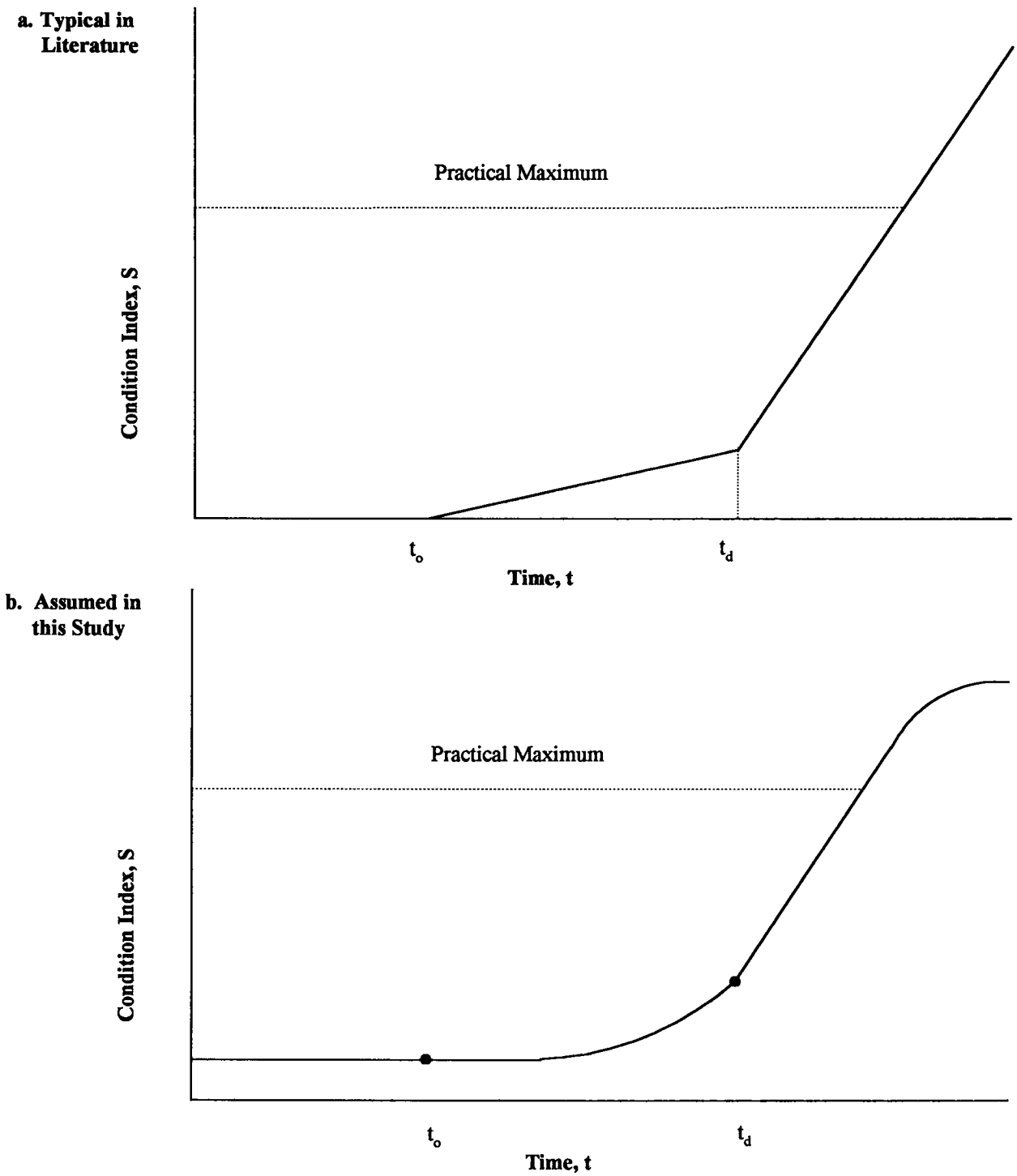
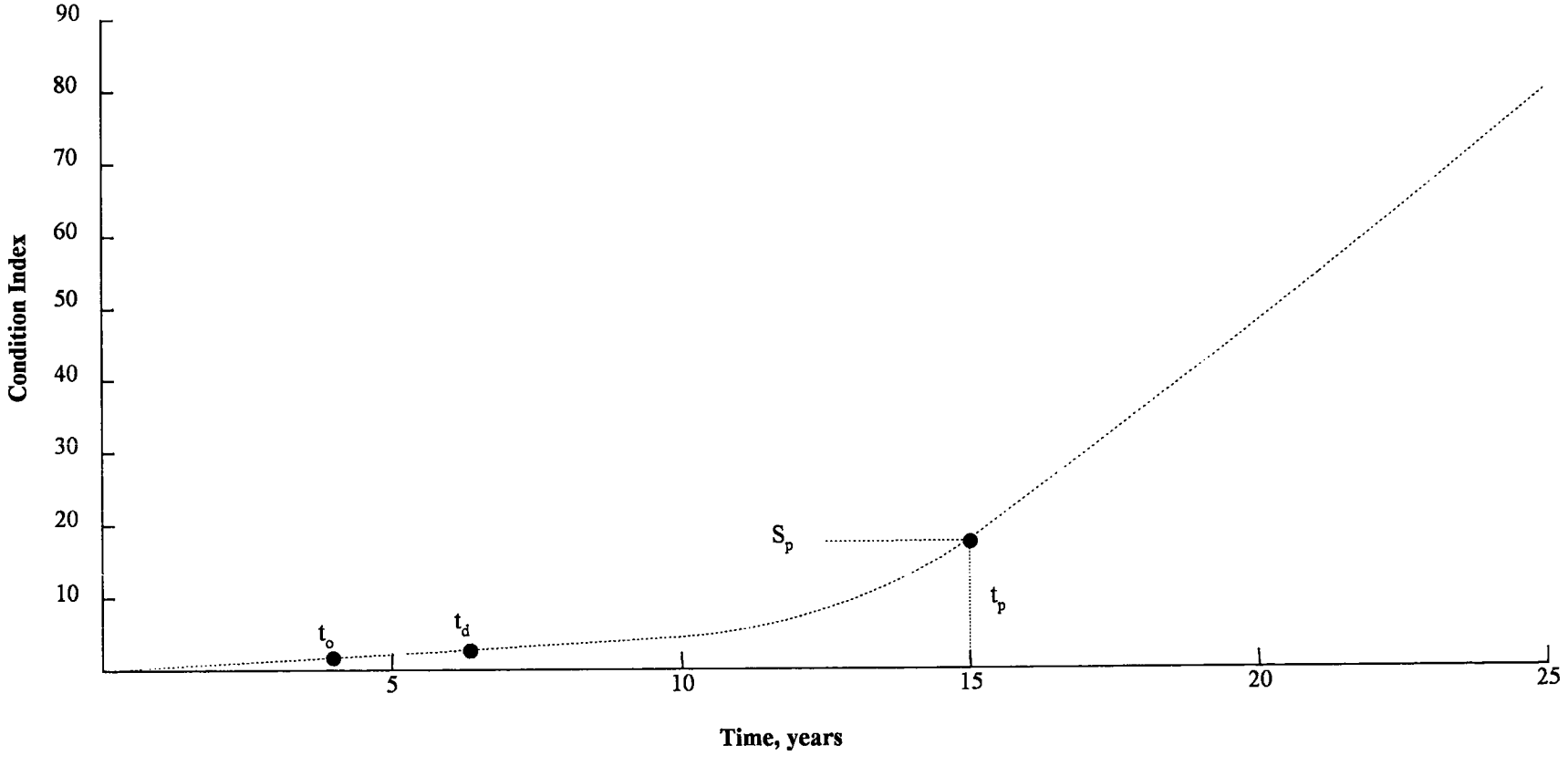


Figure 3. Condition Index by Predictive Model



For this example:
Condition Index S_t = 100 / (1+407.2 (exp(-0.3082 x years)))

2. Condition index at t_d (S_d): 15 percent chloride contamination, 0.5 percent delamination, and 0 percent spalling. Therefore, $S_d = 1.9$.

We do not calculate the concrete age at the initiation of corrosion (t_o) directly. Rather, the concrete age at the initiation of deterioration (t_d) is determined, and then t_o is estimated as follows:

If $t_d > 20$ years: $t_o = t_d - 5$

If t_d is 10 to 20 years: $t_o = t_d - 3.5$

If $t_d < 10$ years: $t_o = t_d - 2$

It should also be noted that although t_o is estimated, it is for information purposes only in this Technical Goal, since it lies too close to t_d to constitute a separate data point. It is, however, used in Technical Goal Four, "Condition Index Versus Time After Treatment."

The age of the concrete at the initiation of deterioration is a required input parameter in all cases, except for concrete components which have previously been repaired. Concrete age at the initiation of deterioration is defined as the time from construction to the first signs of deterioration in form of rust staining, corrosion-induced cracking, delamination, or minor spalling. It typically occurs 2 to 5 years after the initiation of chloride salt-induced corrosion.

The calculation of t_d uses a modified Stratfull formula, which was originally based on field observations and laboratory tests. Input data involve the chloride in the environment, the concrete cover, and the water-cement ratio. Modifications to the original formula include those made by Clear in the 1976 Federal Highway Administration Time to Corrosion Volume 3 report,[1] and the modification in the current study to input the surface chloride level in lieu of the environmental chloride. Appendix D details the formula. Although the formula does not consider diffusion coefficients directly, Weyers and Cady[2] showed that the results are consistent with a diffusion approach. It was chosen for use in lieu of the diffusion approach because 15 years of experience has proven its validity, and the diffusion approach is still considered a developing technology.

In the case of previously repaired concrete, S_r (condition index just after repair) and t_r (concrete age at the time of repair) will replace S_d and t_d, respectively. In the case of concrete which has not reached the stage of visible corrosion-induced deterioration, the present condition index and age do not provide an "appropriate" data point. Therefore, t_d, which will be in the future when a condition index of $S_d = 1.9$ is reached, is estimated, as is t_{45}, age of concrete at the time of the index of 45 ($S_{45} = 45$). Flowchart 1 (Appendix A) presents the overall technical methodology for achieving Technical Goal

One. It shows various modules and decision points involved in a methodology applicable to various concrete members and state of distress. The specifics of each module are presented below.

General Information Module (Flowchart 2)

Certain data are required in all instances. These data will be obtained in the General Information Module as responses to questions, including the following:

Year Constructed? Give the year the concrete was constructed.

Size of Member in Square Feet? For a deck give the top surface area. For other members, give the overall surface area being analyzed.

Type of Member? Deck or Substructure? If a deck is specified, the question is asked: Does the deck have an asphaltic concrete overlay? If the answer is "YES," such is noted in the output so a cost may be assigned to removal of the overlay during treatment.

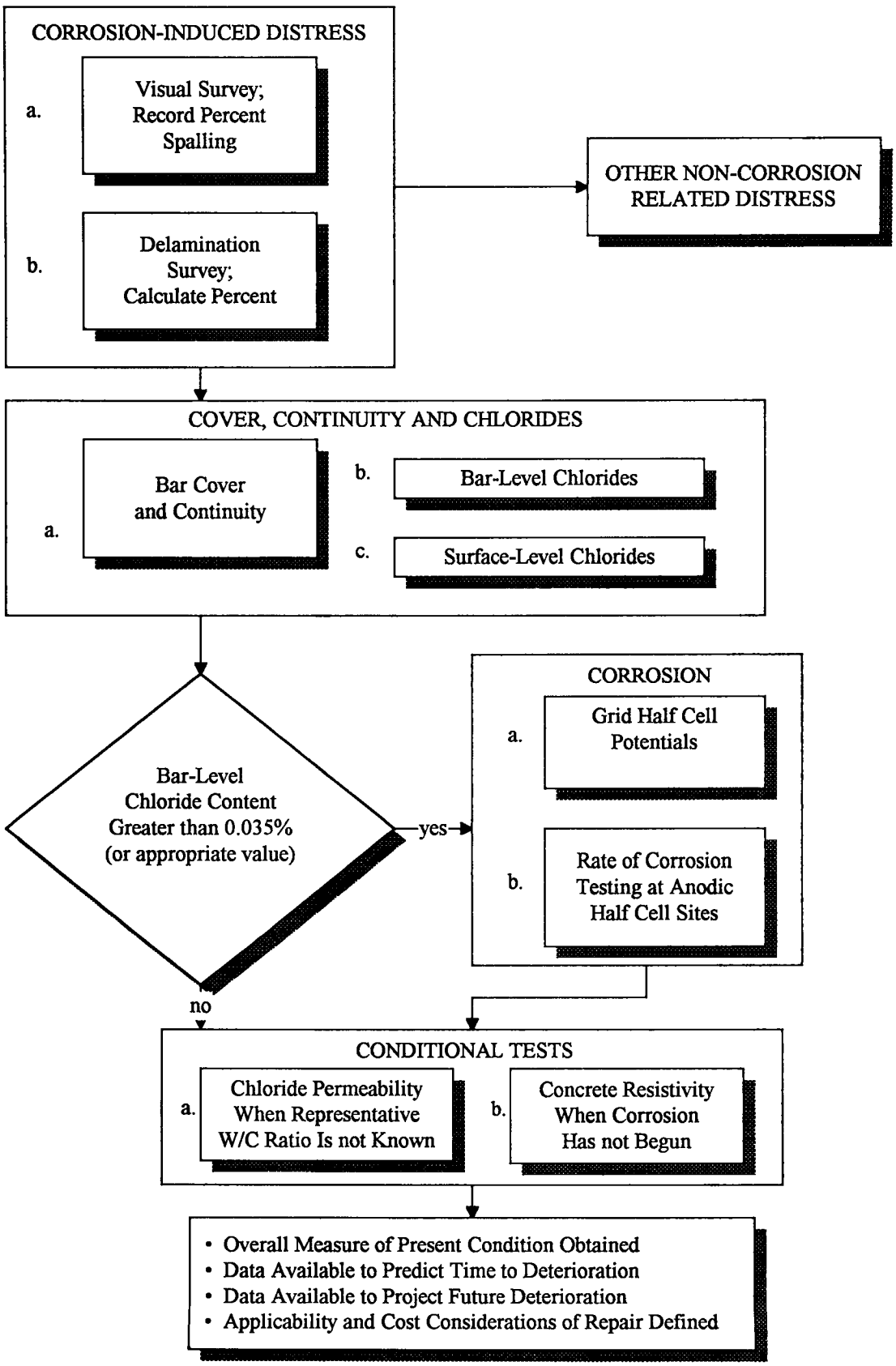
Has the member previously been repaired? Answer "YES" or "NO." If the answer to the question above is "YES," proceed to the Repair Information Module, and then go to the Present Information Module. If the answer is "NO," proceed to the Protect Information, Present Information, and Time-To Modules.

Protect Information Module (Flowchart 3)

This module will ask questions concerning the concrete in the member and the reinforcing steel cover and will ask what, if any, protective systems were used. Findings of a field evaluation are helpful here and are required in the Present Information Module. The recommended field evaluation procedure is summarized in Figure 4. The overall evaluation has four purposes:

1. Obtain an overall measure of present condition.
2. Define data to predict time to deterioration.
3. Develop data to predict future deterioration.
4. Define the applicability and cost considerations for selected treatments.

Figure 4. Evaluation of Field Structures



As a result, the evaluation varies somewhat from that defined in SHRP research by Cady and Gannon.[3] However, this variance is not a conflict, in that the SHRP condition evaluation manual only involves the first item above (i.e., measure present condition). Table 1 compares the evaluation schemes of this research project and of the SHRP condition evaluation manual and notes the reasons for the differences.

Returning to the questions asked in this module:

Question 1: What is the water-cement ratio of the concrete surrounding the reinforcing steel? An answer in the range of 0.2 to 0.7 is required. The ratio may be obtained from project records or by other means. This information will be used to calculate t_d (concrete age at the time of first sign of deterioration) on members which have not been previously repaired if t_d is not otherwise known.

Question 2: Is data on the actual reinforcing steel cover available? If the answer is "NO," the user is asked to input the design cover in inches and the 10th percentile cover value is calculated as the design cover minus 0.48 inches (1.2 centimeters) (a standard deviation of 0.38 inches (0.97 centimeters) is assumed). Of course, the result must be greater than 0. If the answer is "YES," The user is asked to input the cover data and the average, standard deviation, and 10th percentile cover value (average cover - 1.282 * standard deviation) is calculated. The recommended minimum number of cover measurements is 40 per member or per 5,000 square feet (465 square meters), whichever results in the larger number of measurements.

Question 3: Was the concrete constructed with a corrosion protective system listed below, or was one added before the surface-level chloride exceeded the critical value which would later diffuse and cause bar corrosion? (the critical surface chloride value may be obtained using the procedure outlined in Appendix F.) If the answer is "NO," we proceed to the Present Information Module. If the answer is "YES," The following list of possible protective systems is provided, and the user is requested to designate those which are included and to define the years of additional service (i.e., years of additional time to deterioration) which result from each protective system. Note that these years of service are in addition to that provided by the concrete itself which is affected by water-cement ratio and cover depth.

1. Epoxy-Coated Reinforcing Steel
2. Latex-Modified Concrete overlay
3. Concrete Overlay (including low-slump dense concrete)
4. Silica Fume Concrete, Full Depth
5. Silica Fume Concrete, Overlay
6. Waterproof Membrane with Asphalt Concrete Overlay
7. Penetrating Sealer

Table 1. Comparison of Evaluation Schemes

SHRP Condition Evaluation Manual[3]	This Project
1. Concrete Permeability Determining the relative permeability of concrete in the field as in appendix G of Volume 8 (surface airflow).	1. Concrete permeability (and resistivity) AASHTO T277 (and KCC INC Resistivity) AASHTO T277 is required for permeability when representative water-cement ratio of concrete is needed. Reasons: Lack of adequate data relating water-cement ratio and permeability by surface airflow. States are more familiar with AASHTO T277 test method which has a large data base. Resistivity (water saturated, 73 degrees F) is also required, when corrosion deterioration has not begun.
2. Chloride content Recommends procedure applicable to the field. It is given in Appendix F of Volume 8.	2. Chloride content Procedure given in Reference 3 or AASHTO T260-84 procedure for total chloride.
3. Recommended number of samples None, except for cover (40 per member regardless of size).	3. Recommended number of samples A specific number of tests and/or samples are recommended for all variables used in predicting time-to-deterioration. Both "per member" and "per 5000 square feet." requirements.
4. Chloride measurements and/or profiles Recommended only when 10 percent or less of half cell potentials are more negative than -0.20 volt CSE.	4. Chloride measurements and/or profiles Chloride profile data (specifically surface chloride and bar level chloride) are required irrespective of the hal cell potential values.
5. Corrosion rate Recommended only when 90 percent or more of the half cell potentials are more negative than -0.20 volt CSE.	5. Corrosion rate Required when the chloride content at the bar depth is greater than chloride threshold (0.035 percent) and the concrete was repaired/ rehabilitated previously.
6. Half cell potentials Survey done at all times.	6. Half cell potentials Potential surveys are used only to identify the most anodic areas to locate points for corrosion rate measurements when bar-level chloride is greater than chloride threshold (0.035 percent).

8. Surface Protective Coating
9. Concrete with Corrosion Inhibitor Admixture
10. Cathodic Protection
11. Other

Thus, for each protective system designated, the question is asked: How many years will the first signs of deterioration be delayed by the designated protective system? An answer is required, but the effect of the conventional concrete (as defined by its water-cement ratio and the reinforcing steel cover) must not be included in the answer. The answer will be added to t_d from the Pre-Deterioration Submodule, if that module is used.

When a corrosion inhibitor admixture is used as the protective system, an additional question is asked: How much inhibitor is used in the concrete? The Present Module will use the answer to adjust the chloride threshold used in determining the present condition index (S_p) (e.g., 0.035 percent of concrete weight).

For concrete overlays (low-slump dense, latex-modified, and silica fume), the water-cement ratio for input into the t_d formula must be adjusted to reflect the average water-cement ratio of the concrete cover (i.e., part may be overlay and part may be base concrete). To accomplish this, the following questions are asked:

What is the thickness of the overlay?

What is the overlay representative water-cement ratio?

The water-cement ratio of the concrete surrounding the reinforcing steel and the concrete cover is already known. A "prorated average water-cement ratio" will be defined and input (in lieu of the answer to Question 1) into the t_d formula. As an example, if the total cover (per this project's method) is 2.75 inches (7.0 centimeters), the overlay is 2.0 inches (5.1 centimeters), the representative water-cement ratio of the overlay is 0.38, and the water-cement ratio of the base concrete is 0.45, then the input water-cement ratio will be:

$$[(0.38 * 2.0) + (0.45 * 0.75)] / (2.75) = 0.40$$

If more than one protective system is designated (such as epoxy-coated bar and a latex-modified concrete overlay), the years of additional life for each will be added to t_d.

Present Information Module (Flowchart 4)

The Present Information Module is next; it defines the present condition (states of distress). The module first asks for information regarding the age of the member being examined. The following questions are then asked, data entered, and the answers used to calculate the present condition index, S_p.

Question 1: What square footage of the area is spalled (to determine SPALL)?

Question 2: What square footage of the area is delaminated (to determine DELAM)? Do not include spalls.

Question 3: What percentage of concrete samples at reinforcing steel level have chloride content higher than the corrosion threshold (CL)? A minimum of 10 bar level chlorides per member, or per 5,000 square feet (465 square meters) of member surface exposed to salt environment (whichever is greater), is recommended.

Question 4: Are chloride-bearing aggregates involved which have been shown not to contribute chlorides to the corrosion process? Answer "NO" or "YES." If the answer is "YES," input the percentage (by weight of concrete) of "benign" chloride locked in the aggregate.

From the answers to Questions 3 and 4, and with corrosion inhibitor information from the Protect Information Module, the user calculates the percentage of the bar-level chloride values which exceed the total of 0.035 percent (by weight of concrete) plus the aggregate benign chloride plus the corrosion inhibitor offset.

Then, the present condition index, S_p, will be calculated as [CL + (2.5 * DELAM) + (7.5 * SPALL)] / 8.5, corresponding to the age of the concrete at preset, t_p. This completes the Present Information Module. Then the Time-To Module follows.

Time-To Module (Flowchart 5)

The results of the Present Information Module calculation of S_p are checked. If S_p is greater than 1.9, it is concluded that t_d occurred in past, and we proceed to the Post-Deterioration Submodule. If S_p is less than 1.2, proceed to the Pre-Deterioration Submodule. If S_p is between 1.2 and 1.9, t_d is defined as equal to t_p, and another data point at some time in the future will be defined via the Calculation Two Submodule.

Starting with the Post-Deterioration Submodule:

Post-Deterioration Submodule (Flowchart 6)

The submodule asks for technical "input data" regarding the time to deterioration.

Question 1: From the present data, it has been determined that this member is showing signs of corrosion-induced deterioration. What year was chloride-induced corrosion first noticed? Possible answers are "Year," or "Don't Know." If a year is given, it is accepted (and t_d = Year Given minus Year Built), no other background data are requested, and the user proceeds. If the answer is "Don't Know," proceed to the Calculation One Submodule, knowing that t_d must lie between the Year Built and the Present.

Calculation One Submodule (Flowchart 7)

In this submodule the user calculates the "past" t_d. Input data include that from the General, Protect, and Present Information Modules as follows:

1. Adjustment of t_d, if any, because of a protective system installed at the time of initial construction.

2. Average, standard deviation, and 10th percentile concrete cover.

3. Water-cement ratio of the concrete between the surface and bar.

The module then requests data on the surface chloride level at present to calculate t_d for the concrete. The methodology recommends that at least eight surface chloride levels (from 0.25 inches (0.6 centimeters) to 0.75 inches (1.9 centimeters)) be determined per member or per 5,000 square feet (465 square meters), whichever results in the larger number. Surface chloride samples must not be taken in patched areas. Upon receipt of these data, "t" is calculated as the "Year Data Taken" minus "Year Concrete Built" and t_d is calculated from the formula presented in Appendix D and adjusted per the first item above.

Pre-Deterioration Submodule (Flowchart 8)

When considered t_d in the future, the same input items are requested or obtained from the other modules as for the Post-Deterioration Submodule. However, if the surface chloride values are extremely low because of lack of exposure age, the calculation of t_d will be incorrect. Therefore, the surface chlorides are checked after they are entered. If

the average is greater than or equal to 0.10 percent of chloride by weight of concrete, proceed as per the Post-Deterioration and Calculation One Submodules. If the average is less than 0.10 percent, proceed to the Adjust Submodule as follows.

When the surface chlorides are quite low, the user needs an estimate of surface chloride values in 10 years. To aid in this estimate, input the mean annual snowfall in inches in the vicinity of the structure and then answer the subsequent questions as well.

Is the concrete exposed to a marine environment, YES or NO?

If the answer to the marine environment question is "YES," answer another question: Is the member within 25 feet (7.6 meters) of the seawater?

Based on the above responses and the following table, the surface chloride level 10 years into the future is estimated. Known data include the question answers, the present surface chloride (Z_t), and the exposure age to date (t).

Snow Range* (inches)	Seawater* Exposure	Surface Clorides in 10 years, % Greater of:
0 to 3	No	$[Z_t * (t+10)/t]$ or 0.04%
3 to 12	No	$[Z_t * (t+10)/t]$ or 0.10 %
0 to 12	Yes > 25 ft	$[Z_t * (t+10)/t]$ or 0.10 %
0 to 12	Yes < 25 ft	$[Z_t * (t+10)/t]$ or 0.25 %
>12	No	$[Z_t * (t+10)/t]$ or 0.25 %
>12	Yes > 25 ft	$[Z_t * (t+10)/t]$ or 0.35 %
>12	Yes < 25 ft	$[Z_t * (t+10)/t]$ or 0.45 %

* One inch is 2.54 centimeters; one foot is 0.305 meters.

Then t_d is calculated based on the appropriate Z_t from the table above, while "t" in the equation for Z_t is equal to "present t" (concrete age at the time of measuring surface chlorides) plus 10 years.

Calculation Two Submodule (Flowchart 9)

The user then must continue the Pre-Deterioration Submodule to estimate the concrete condition at some time in the future after t_d. This is done using the Calculation Two Submodule. This estimate is required to determine the slope of the deterioration versus time curve after corrosion is active. By this time, chloride is present at the reinforcing steel level in excess, and the corrosion and deterioration rates will be dictated by many factors, including the steel concentration, oxygen availability, and the resistivity of the concrete in the field. All these factors are not known. However, an estimate of whether the deterioration rate will be low, medium, or high should be possible, and standard curves can be assigned to each rate designation. This assignment can be based on the

wet resistivity of the concrete. A suggested test method, is presented in Appendix E. The following table provides decision data.

Distress Rate	Resistivity ohm-cm	Years to Condition Index of 45
High	< 7,500	t_d + 10
Medium	7,500 to 30,000	t_d + 20
Low	> 30,000	t_d + 35

From the table above, t_{45} the concrete age, to reach the index of 45 (S_{45} = 45) prior to rehabilitation, can be defined and output to the cost analysis in lieu of t_p and S_p. The estimates in the table above are based on experience. Examples and a sample plot are presented in Appendix E.

Repair Information Module (Flowchart 10)

This module covers concretes which were repaired in the past in response to corrosion induced damage. The past repair includes patching (salt contaminated concrete may be left in place or removed), sealing, overlay, and/or membrane. It does not include cathodic protection.

These concretes have t_d (age of concrete at the first signs of deterioration) in the past. Therefore, there is no need to calculate t_d or to define t_o (age of concrete at the initiation of corrosion). To accomplish Technical Goal One, however, the user needs the following information.

1. Year in which the previous repair was performed.

2. Details of the previous repair including

    a. percent bar-level chloride contamination just after repair;

    b. percent delamination just after repair;

    c. percent spalls just after repair; and

    d. type of protection applied at repair.

3. Details of the present condition including percent bar-level chloride contamination, percent delamination, and percent spalls; from Present Information Module.

We know the age of the concrete at the time of the previous repair, t_r. From Item No. 2 above, we can calculate the concrete condition index just after the previous repair, S_r, as follows.

$$S_r = [(\text{Item 2.a}) + (2.5 * \text{Item 2.b}) + (7.5 * \text{Item 2.c})] / 8.5 \qquad \text{(Eq. 2.3)}$$

The user also knows the present condition index, S_p, and the concrete age at the present time, t_p, from the Present Information Module. From these data, the user can fit the condition index versus concrete age equation. An example of this procedure follows.

Assume a bridge deck was repaired by removal and repair of all delaminations and spalls in 1985. Bar-level chloride contamination just after the repair was 75 percent, delamination was 0 percent, and spalling was 0 percent. Thus, the condition index just after repair is:

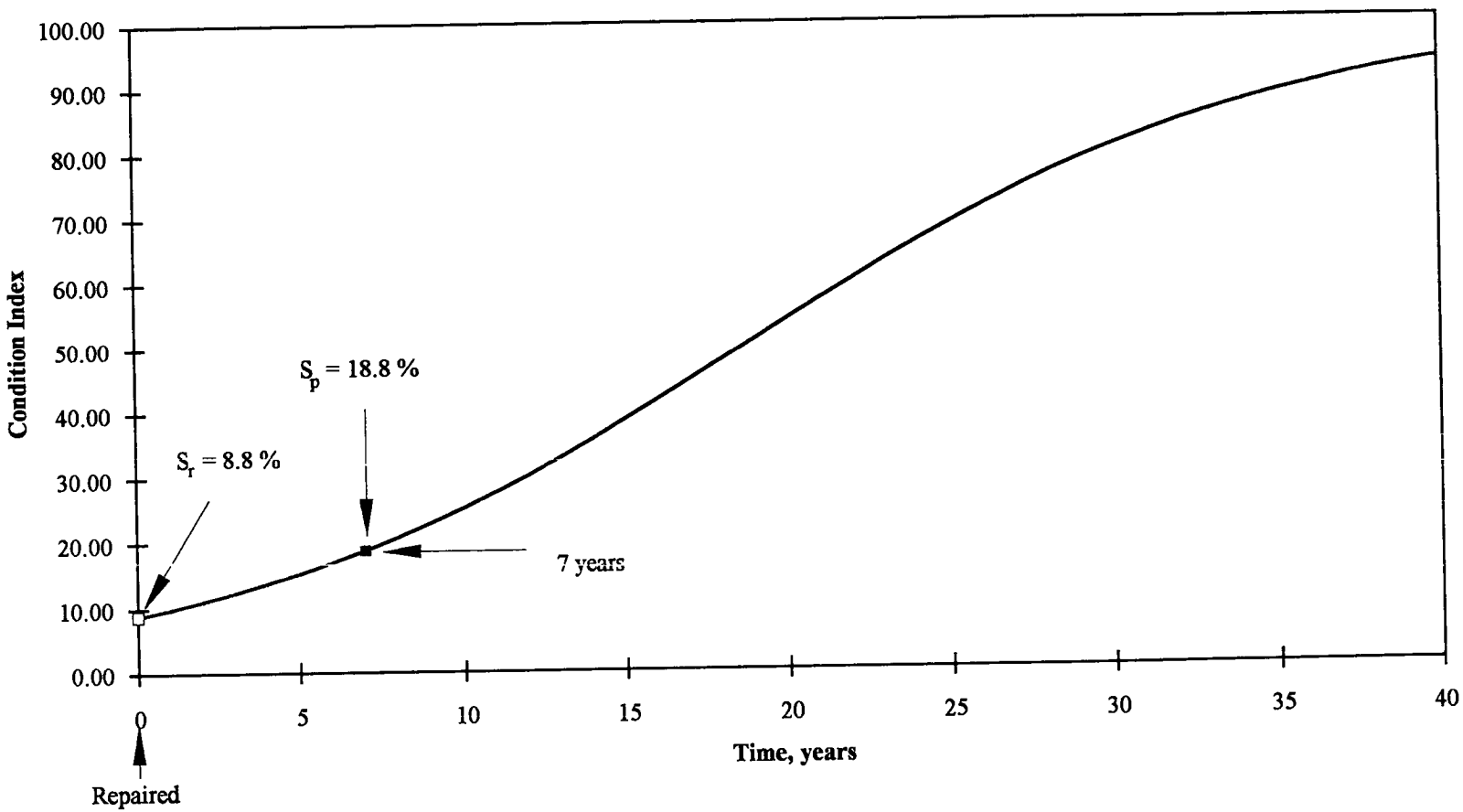
$$S_r = [CL + 2.5\ (DELAM) + 7.5\ (SPALL)] / 8.5$$
$$S_r = [75 + 2.5\ (0) + 7.5\ (0)] / 8.5$$
$$S_r = 8.8$$

Since the condition index prior to the repair is not of interest, only for the purpose of the plot of index versus time, it may be assumed that the age of the concrete at repair, t_r, is 0. Presently, bar-level chloride contamination is 90 percent, delamination is 16 percent, and spalling is 4 percent. Thus, the condition index at present, is:

$$S_p = [CL + 2.5\ (DELAM) + 7.5\ (SPALL)] / 8.5$$
$$S_p = [90 + 2.5(16) + 7.5\ (4)] / 8.5$$
$$S_p = 18.8$$

Consistent with the assumption for the age of concrete at the repair, the age of concrete at the present, t_p, is 1992 - 1985 = 7 years. A plot of these results using the condition index versus concrete age equation is presented in Figure 5. The condition index (see Equation 2.2) used for Figure 5 is $S_t = 100 / (1 + 10.36\ (\exp\ (-0.125*\text{years})))$.

Figure 5. Sample Condition Index Curve for a Previously Repaired Structure



3. Technical Goal Two

Decomposing Condition Index

Condition index (or distress index), S, needs to be decomposed into its component parts (i.e., percent chloride contamination, percent delamination, and percent spalling) at various points in the future for the purpose of estimating treatment cost. This can best be accomplished by applying a series of "rules," or "ratios," as listed below.

1. For all deck concrete except those with 1-inch (2.54 centimeters) or thicker, concrete overlays: DELAM is 4 times SPALL. For all deck concrete with 1-inch (2.54 centimeters) or thicker bonded concrete overlays: DELAM is 8 times SPALL.

2. For all non-deck concrete except those with 1-inch (2.54 centimeters) or thicker concrete jackets or shotcrete: DELAM is 8 times SPALL. For all non-deck concrete with 1-inch (2.54 centimeters) or thicker concrete jackets or shotcrete: DELAM is 16 times SPALL.

3. For all concrete: bar-level chloride contamination (CL, percent of total area) increases linearly from 0 at condition index of 0 to 100 at condition index of 20 (i.e., 5 percent CL increase for each index increase of 1). Bar-level chloride contamination remains at 100 percent when the index is greater than 20.

As an example, assume a non-overlay deck is predicted to have a condition index of 12 sometime in the future. What will be the amount of total deterioration at that time?

CL is predicted to be : 12 * 5 = 60
CL portion of the index is: 60/8.5 = 7.06
Then, "DELAM + SPALL" portion of the index is: 12 -7.06 = 4.94
Or, stated differently: 4.94 = (2.5 * DELAM + 7.5 SPALL) / 8.5
Whereas, for non-overlay decks: DELAM = 4 * SPALL
This will give: DELAM = 9.60, and SPALL = 2.40

Thus, the total deterioration = DELAM + SPALL = 9.60 + 2.40 = 12.00
Percent of deck area

Although research would be required to completely validate the "rules" stated here, they are technically logical and therefore, meet the present need.

In the area of cost calculations, the following point should also be considered. The actual delaminations which exist and the concrete which is removed prior to patching are not equal. This is because it is necessary to "square off" the removal areas (for saw-cutting, etc.). Also some new delaminations are created by the removal process or occur during the delay between the survey and contract execution. This increase in delamination affects cost. Therefore, for cost calculations, the quantity (square feet or percent) of delamination should include an increase factor of 1.2 (i.e., 20 percent increase).

4. Technical Goal Three

Cost and Maximum Service Life of Treatment

4.1 Agency Costs

Agency costs are those directly associated with the construction of various treatment procedures. Agency costs should be known in order to select the most cost-effective alternative and determine its timing. Construction cost can vary significantly from one area to another and from time to time, depending on many factors. The user is the most reliable source of information regarding cost of a certain treatment in a given jurisdiction. However, the user with no previous experience with construction costs may consult SHRP research by Wyers, et al.[4] and by Bennett, et al.[5]

Four types of costs are included in the methodology, as listed below:

1. Lump sum costs (e.g., mobilization).

2. Fixed costs (dependent on fixed member area, e.g., dollar per square foot).

3. Variable costs (dependent on variable distressed area):

   a. dollars per square foot of spalled areas.

   b. dollars per square foot of delaminated areas.

   c. dollars per square foot of chloride contaminated areas.

4. Maintenance costs (only for monitoring and maintaining cathodic protection in this methodology).

4.2 User Costs

Two types of user costs are included in the methodology:

1. during-treatment costs.

2. prior-to-treatment and subsequent-to-treatment costs.

During-Treatment Costs

Costs during the treatment are related to congestion, as influenced by the degree of bridge closure and the duration of the construction. Use Equation 4.1 to find user costs resulting from the degree of bridge closure.

$$U_1 = K_1 \, t_t \, t_c \, q_o \qquad \text{(Eq. 4.1)}$$

where

U_1 = user costs during the treatment period, dollars

K_1 = value of bridge user time while traveling, dollars per minute per vehicle

t_c = duration of treatment, days

q_o = average two-way daily traffic volume across the bridge, vehicles per day

t_t = increment in travel time across the bridge (or in detour around the bridge) caused by construction, minutes

For traveling across the bridge, t_t may be obtained from Equation 4.2.

$$t_t = 0.15 \, t_f \, [(q_o / C1)^4 - (q_o / C)^4] \qquad \text{(Eq. 4.2)}$$

where

t_f = free-flow travel time across the bridge, minutes

C1 = two-way capacity of the bridge during construction, vehicles per day

C = two-way capacity of the bridge during normal periods, vehicles per day

Prior-to-Treatment and Subsequent-to-Treatment Costs (Decks Only)

Costs in the period prior to treatment are a function of the condition of the bridge deck and its effect on traffic flow. A badly spalled deck would impede traffic flow, causing speed reductions, congestion, and an increase in travel costs and vehicle operating costs. Use Equation 4.3 to find user costs due to worsening deck condition for a given year.

$$U_2 = K_2 [S / S_m]^{n_o} [365 q_o] \quad \text{(Eq. 4.3)}$$

where:

U_2 = user costs due to worsening deck condition, dollars per year

K_2 = a calibrating constant, dollars per vehicle

[$K_2 = a\ t_f\ K_1$: See "During-Treatment Costs," above, for definitions of K_1 and t_f. Parameter "a" is the percentage of free-flow travel time, t_f, across the bridge, representing the increment in travel time when $S = S_m$.]

S = concrete condition index for the year considered

S_m = maximum tolerable condition index (see Section 5.2)

q_o = average two-way daily traffic volume across the bridge, vehicles per day

n_o = typically 4

4.3 Maximum Possible Service Life of a Treatment

The maximum possible service life of a treatment (e.g., sealer, overlay, etc.) depends on the durability of the treatment itself and is independent of the corrosion-induced deterioration of the underlying reinforced concrete. The bridge environment also affects the maximum possible service life of a treatment. The level of traffic (for decks) and the weather condition (e.g., freeze/thaw, wet/dry) have a definite role in the durability of various treatments. The user should provide the maximum possible service life of a

selected treatment based on the factors discussed. The user with no previous experience with the service life of the treatment may consult Wyers et al.[4]

5. Technical Goal Four

Condition Index Versus Time After Treatment

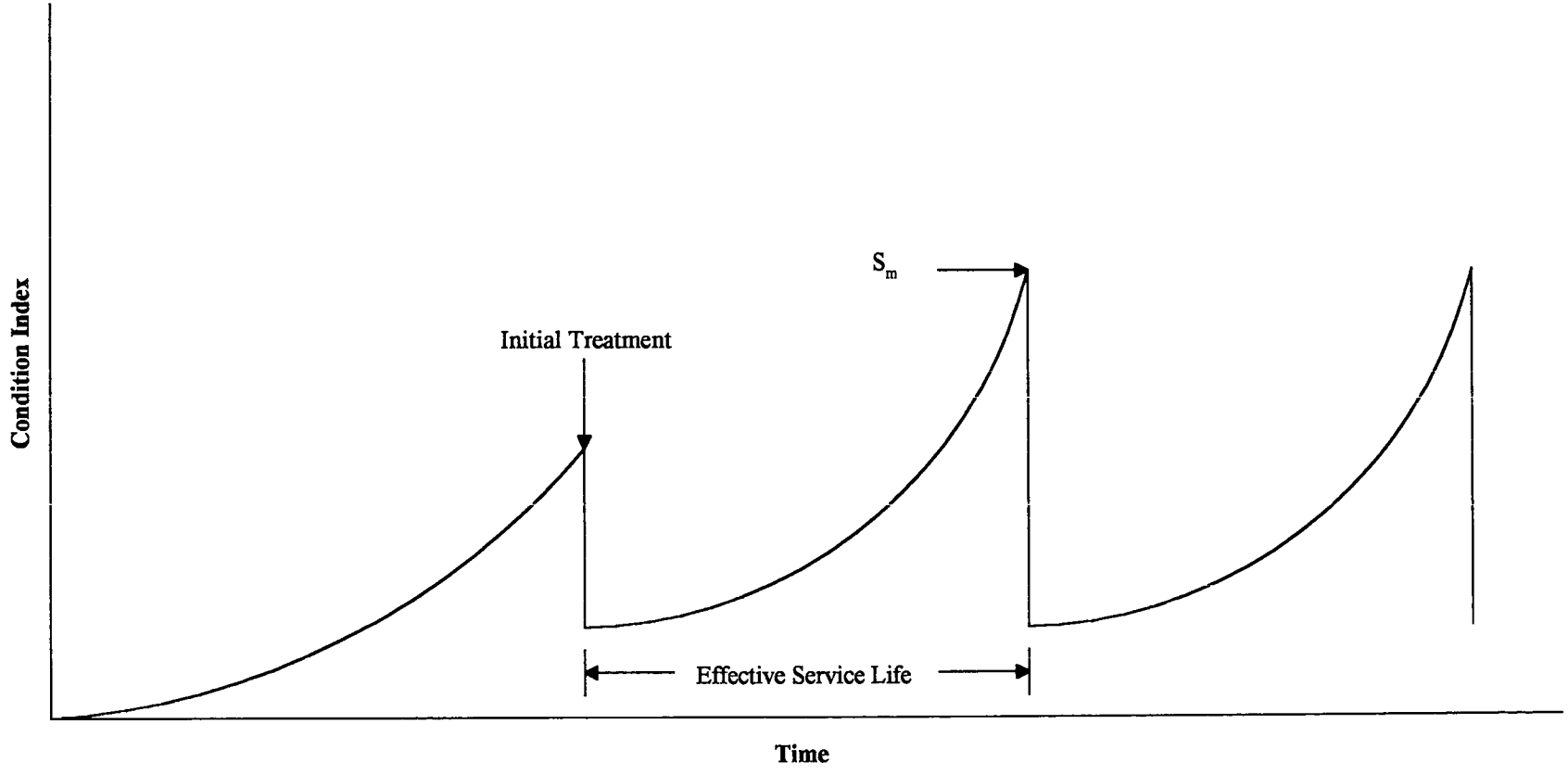
This technical goal is similar to Technical Goal One in that two points on the "after treatment" condition index versus time curve are required for each treatment cycle. The first point is immediately after treatment (in time) but at a lower distress level (because the physical distress in most cases is patched). The second point is at the maximum tolerable condition index, S_m.

In theory, the only way to determine the proper time to perform the second treatment would be to scan all possible combinations of first and second treatments and to determine the life-cycle cost for each combination. Resulting in a very large number of calculations, this method would be impractical, especially for the handbook version of this task. To avoid this, the trial calculations were made, and the S_m point was chosen for all second treatments (see Figure 6).

5.1 Condition Immediately After Treatment; First Point on Curve

One must first determine the immediate effect of the treatment on the condition index. By its nature, the treatment will generally reduce the condition index. This is accomplished through repairing delaminations and spalls and removing, or neutralize effect of the chlorides. This study assumes that all delamination and spalls will always be repaired. Thus, different treatments vary mainly in their effect on bar-level chloride contamination. The index can be reduced if all the steel was never chloride contaminated, or if the chloride contamination is removed or neutralized. The information from Technical Goal Two (Decomposing Condition Index) can be used to predict the level of chloride contamination at the time of the treatment so that the "immediately after treatment" condition index can be calculated.

Figure 6. Condition Versus Time Before and After Treatment



5.2 Maximum Tolerable Condition; Second Point on Curve

The maximum tolerable condition index, S_m, is specified based on engineering factors. It depends on the structural features of the component as well on as the ride quality of the deck. Initially, it was decided that the maximum tolerable condition index should not exceed 45 for bridge decks when ride quality is the criterion. However, considering safety factors and user costs, the recommended absolute maximum tolerable index is 80 percent of the index of 45, or an index of 36 (i.e., 0.8 * 45 = 36). (Note that the maximum tolerable condition index also applies to pre-treatment condition, Technical Goal One.)

The most important information to determine is the effective service life of the treated concrete (the period of time after which the condition index of the treated concrete reaches S_m).

Effective Service Life After Treatment

The time of treatment can affect the effective service life of the treated concrete. As noted in Figure 1, the treatment can be forced to occur at the present point in time (Best Action Now), or the system can define the best action at the best time in the future by minimizing life-cycle costs. Regardless of the approach taken, the effective service life of each candidate treatment must be known.

SHRP research[4] indicated that for at least some treatments, the life of the treatment was not primarily determined by the treatment itself but depended on characteristics of the concrete which was repaired. Typically, non-electrochemical treatments experience shorter lives when placed on bridge components with much remaining salty concrete and high bar corrosion rates than when placed on components with low chlorides and low corrosion rates.

This information became the primary determinant of the after treatment approach in this work. For example, an overlaid deck does not have a fixed effective service life; rather, it has a variable effective service life, dependent on the corrosion state of the reinforcing steel when the overlay is placed. Because of this finding, after-treatment approach was developed, involving the corrosion rate of the reinforcing steel. The approach is based on knowing the corrosion rate versus time and on repeating of each chosen treatment after an additional amount of cumulative corrosion (corrosion rate multiplied by time) has occurred. The additional amount of cumulative corrosion equals that which would have occurred from t_o (time to initiation of corrosion) to t_m (time to maximum tolerable condition, if concrete was not treated).

The first step is to construct (and extend) the before-treatment corrosion rate versus time curve. The area beneath that curve up to the corrosion rate corresponding to S_m

(i.e., C_m) is then calculated. That area represents the cumulative corrosion. The corrosion rate immediately prior to the initiation of corrosion is known to be 0. Based on field evaluations, an assumption can be made that the before-treatment corrosion rate versus time curve is a straight line extending upward from 0 at t_o to the corrosion rate corresponding to S_m (i.e., C_m) and through the present time corrosion rate (i.e., C_p). To calculate the area under the corrosion rate line from t_o to C_m, the following steps should be taken:

1. Determine t_m, the age of the concrete at which a condition index of S_m (or index of 36, if selected) is expected, from the "pre-treatment" index versus time curve of Technical Goal One.

2. Calculate the years between time to initiation of corrosion and time to maximum tolerable condition index (i.e., $t_m - t_o$).

3. Calculate the yearly rate of increase in corrosion rate by dividing the present corrosion rate (C_p) by the years between t_p (age of concrete at present) and t_o.

4. Calculate the corrosion rate at the time of maximum allowable condition index (C_m) by multiplying the result of Item 2 by the result of Item 3.

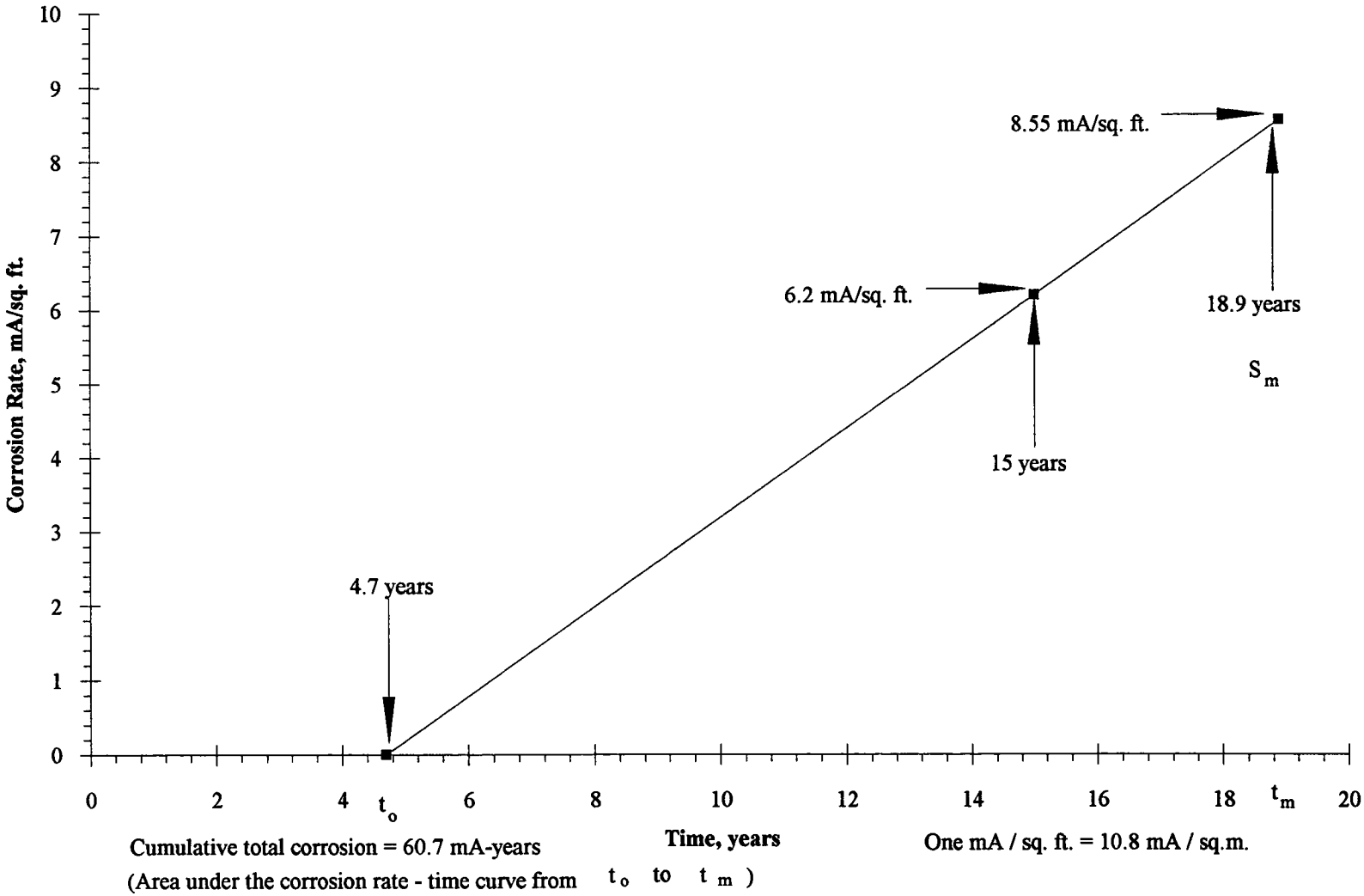
5. Determine the area under the corrosion rate line (from t_o to t_m) in milli-amperes per square foot–years (i.e., 0.5 * Item 2 * Item 4).

As an example, for the case in Figure 7, a condition index of S_m = 36 was projected from the condition versus time curve to occur at 18.9 years (Item 1). Corrosion initiation occurred at 4.7 years; thus, Item 2 is 14.2 years (18.9 yrs - 4.7 yrs). The field evaluation yielded a corrosion rate of 6.2 milli-amperes per square foot (66.7 milli-amperes per square meter) of bar at 15 years. The yearly rate of increase in corrosion rate since initiation (Item 3) was 0.602 milli-amperes per square foot per year (6.5 milli-amperes per square meter per year) (6.2 mA/sq ft/ (15 yrs - 4.7 yrs)). The corrosion rate at S_m = 36, C_m (Item 4), would be 8.55 milli-amperes per square foot (92.0 milli-amperes per square meter) (0.602 mA/sq ft/yr * 14.2 yrs). Then, the area under the corrosion rate line from t_o to t_m is 60.7 milli-amperes per square foot-years (653.4 milli-amperes per square meter-years) (0.5 * 14.2 yrs * 8.55 mA/sq ft).

Thus, the effective service life of any treatment on the example concrete will be the shorter of the following:

1. the maximum possible service life of the treatment, independent of corrosion.

Figure 7. Corrosion Rate Versus Time



2. the time required for additional cumulative corrosion equal to the area under corrosion rate line from t_o to t_m (60.7 milli-amperes per square foot-years (653.4 milli-amperes per square meter-years) in the example above) to take place

Technical Goal 3 discusses Item 1, above. Determining Item 2, requires data concerning the effect of the treatment on the corrosion rate. Figure 8 depicts four different possible effects of a treatment on the rate of corrosion. In Case 1, the corrosion rate continues to increase at the same rate as before the treatment. In Case 2, the corrosion rate is frozen at the value when treatment was performed. In Case 3, the corrosion rate practically drops to 0 as soon as the treatment was performed; and in Case 4, the corrosion rate decreases slowly with time. Each candidate treatment will be assigned a default number based on the trend of rate of corrosion line (i.e., slope of the line) after the treatment, and the system user will be able to adjust the numbers.

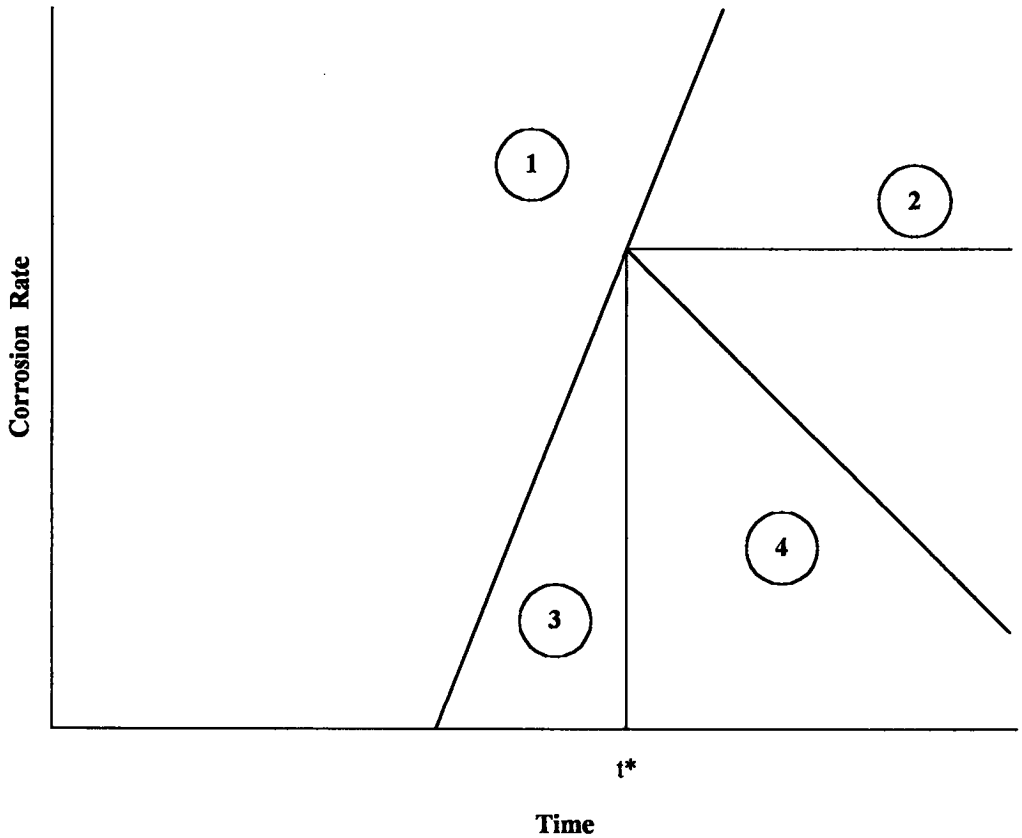
Once the shape of the after-treatment corrosion rate line is defined, it is a relatively simple mathematical calculation to determine the number of years required to equalize the area under the after-treatment line with the area under the before-treatment line, as discussed in Item 2, above. Figure 9 presents an example for the case in which the corrosion rate is frozen at the before-treatment value. The effective service life after the treatment can be obtained when Areas A_1 and A_2 are equalized.

Derivation of the equations for the effective service life after the treatment for various cases, as documented in Part II of this report, indicated that when Areas A_1 and A_2 are equalized (see example in Figure 9) the rate of corrosion is canceled out. The effective service life then depends on the ratio of the slope of the after-treatment corrosion rate line to the slope of the before-treatment corrosion rate line. Considering this, each candidate treatment will be assigned a default number based on the ratio discussed, and the system user will be able to adjust the ratio numbers.

Special Characteristics of "Bare" Concretes Treated with Rigid Overlays

Concrete treated with overlays has a special characteristic: the overlaid structure does not spall as readily as a structure without the overlay. When the cover is greatly increased and exceeds about 2.5 to 3 inches (6.3 centimeters to 7.6 centimeters), there is a less of tendency for the delamination to break-up and for spalls to occur. Thus, when a bonded concrete overlay (or "jacket" in the case of substructures) thicker than 1 inch (2.54 centimeters) is added, more cumulative corrosion is required for a given condition index to develop than was required before overlay placement. This effect may be included when constructing the after-treatment condition index versus time curve, depending on the accuracy of the results of life-cycle cost analysis. To do so, consider the following:

Figure 8. Impacts of Various Treatments on Corrosion Rate



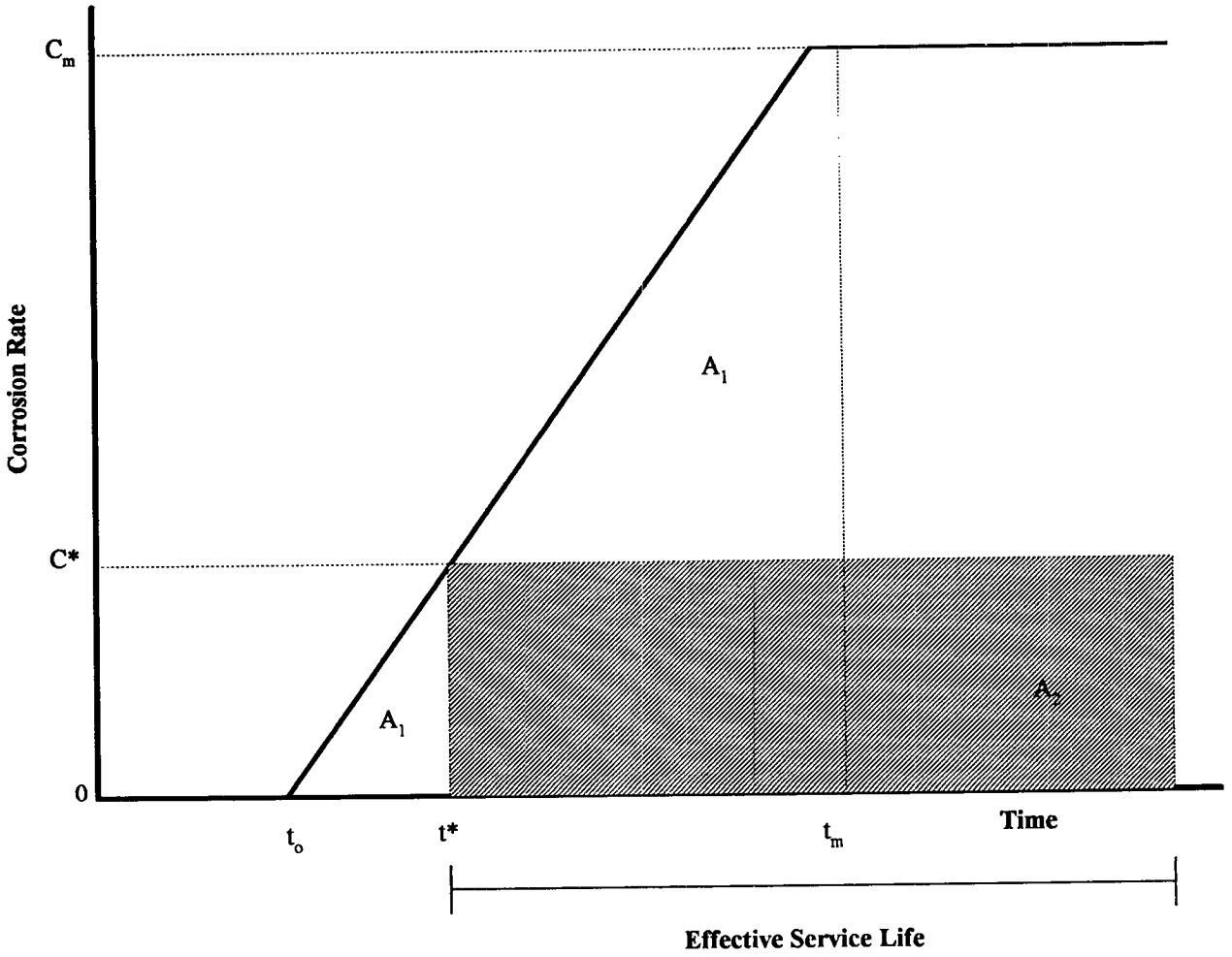
Case 1. Rate of Corrosion continues to increase.

Case 2. Rate of Corrosion levels off.

Case 3 Rate of Corrosion practically drops to zero.

Case 4. Rate of Corrosion decreases slowly with time.

Figure 9. Procedure to Estimate Life of Treated Concrete When Corrosion Rate is Held Constant



C_m = Corrosion Rate at Maximum Allowable Condition

C*= Corrosion Rate at Treatment

- SPALL have three times the weight of DELAM in the condition index equation.

- With a bonded concrete overlay (thicker than 1 inch (2.54 centimeters)), SPALL will form at only about half the rate they would have formed had the overlay not been present, DELAM will form at the same rate.

As an example, assume a deck XX years after treatment. Assume that without an overlay, it has CL=100, DELAM=16, SPALL=4, and a condition index of S=20. With an overlay, it would have CL=100, DELAM=16, and SPALL=2, yielding a condition index of S=18.2. Thus, the difference is only 1.8 units, or 9 percent. If the CL was 50, the difference would still be only 1.8 units, but the percentage difference would be 13 percent.

If it is decided that this effect should be included in the prediction of the effective service life after the treatment, two approaches may be taken. The first is to appropriately increase the area under the corrosion rate line after the treatment. The other is to decrease the slope of the "after treatment" condition index versus time curve, such that additional time is realized until S_m is reached ($S_{overlay} = S_{no} - 0.44$ SPALL).

Effective Service Life of Previously Treated Concrete

The "same total corrosion since initiation" philosophy is not literally applicable is the case of previously treated members. A special procedure for these concretes is described below.

The present corrosion rate (C_p) can be measured and it is known. But the corrosion rate at the past treatment (C_r) is not known, and neither is t_o or t_d, for which we have assumed corrosion rates in other analyses. Therefore C_r needs to be estimated. To do so, we must rely on trends for the type of treatment done. We know that

1. if a sealer, membrane, or overlay was installed, the corrosion rate has remained relatively constant;

2. if none of the above items were used, the corrosion rate has increased since treatment; and

3. since a treatment was previously performed, the corrosion rate at that time had to be greater than 1 milli-ampere per square foot (10.8 milli-amperes per square meter).

Thus, the corrosion rate at treatment needs to be defined as follows:

- If Item 1 above applies, the corrosion rate at treatment (C_r) is equal to the corrosion rate at present (C_p).

- If Item 1 above does not apply, the corrosion rate at treatment (C_r) is equal to the greater of the following:

  1 milli-ampere per square foot (10.8 milli-amperes per square meter), or
  $(C_p * S_r) / S_r$

where

S_r = concrete condition index just after previous treatment

S_p = concrete condition index when C_p is measured

Continue the evaluation as for concretes which were not previously treated.

Rate of Corrosion Measurement

The evaluation presented above includes measuring the corrosion rate, C_p. For cases in which the bar-level chloride exceeds 0.035 percent by weight of concrete, the corrosion rate is determined at anodic (most negative half cell potential) locations. Ten measurement locations per member or per 5,000 square feet (465 square meters), whichever is greater, are recommended. The average and standard deviation are determined, and the 90th percentile corrosion rate value is defined as the average plus 1.282 times standard deviation. Finally, the steel density within the member is examined and rated as high, medium, or low; the 90th percentile corrosion rate value is appropriately adjusted to reflect a value per square foot of member surface. See Part II, Chapter 4.

SHRP research evaluated three different rate of corrosion devices. They yield different, but related results. This project's examples deal with only one of those devices (i.e., KCC, Inc., device). Thus, data obtained using the other two devices (i.e., NCS device by Nippon Steel Corporation, and Gecor Device by GEOCISA) must be converted on the front end to the equivalent KCC, Inc., device value.

Effective Service Life of Concrete with Preventive Treatment

Preventive treatment can be initiated prior to significant chloride contamination. Preventive treatment extends the effective service life of the concrete by stopping or slowing additional salt intrusion. The equal cumulative corrosion procedure is obviously not applicable in these instances, since the treatment is applied prior to the time of initiation of corrosion, t_o. Therefore, a separate procedure has been defined, as discussed in Appendix F.

6. Technical Goal Five

Life-Cycle Cost Analysis

Having determined: (1) the concrete performance before treatment, (2) the various costs associated with a treatment, and (3) the concrete performance after treatment, the user must now decide what type of treatment to apply and when to apply it to achieve minimum life-cycle cost. Technical Goal Five deals with this subject through life-cycle cost analysis.

6.1 Overview

For each feasible treatment alternative, the optimal timing of treating the concrete yielding the lowest discounted life-cycle cost (both agency costs and user costs), will be determined. The user can then compare treatments on the basis of their recommended times of performance and their predicted minimum life-cycle costs, in order to select the treatment to be actually used. In many cases, the recommended activity may be the one that has the best cost results (i.e., its optimal life-cycle costs are the lowest among those of all activities considered). In some cases, however, other factors may influence a decision: such as the local availability of a repair technology, or budget constraints that dictate both the level and the timing of anticipated expenditures.

Two methods of life-cycle cost analysis have been used. The first method, based on a capitalized cost approach, has been devised for the computer program version of the methodology. Since this method is not suitable for a handbook solution, the second method, based on a salvage value approach, has been devised for the handbook version of the methodology. In both methods, life-cycle cost is determined in terms of present worth.

In the computer method, an indefinite planning horizon is considered so that the salvage value of the last cycle of treatment will be negligible and therefore need not to be determined. However, in the handbook method a 20-year planning horizon is considered, and a method to obtain the salvage value of the last cycle of treatment is provided. Obviously, because of the difference in the duration of the planning horizon,

the life-cycle cost of a given treatment will not be the same using these two methods. However, the critical factor in the methodology is the difference in life-cycle cost, not the actual value of the life-cycle cost. The two methods give the same relative life-cycle costs and result in the same answer for the optimum treatment and its timing.

In the computer method, life-cycle cost for a given treatment, is determined for treating concrete in each consecutive year between the present time and the time corresponding to the maximum tolerable condition index. This is done for the purpose of life-cycle cost comparison, to determine the optimum time of treatment. For simplicity, in the handbook method, for a given treatment, the user only considers treating the concrete at only three different points in time for the purpose of life-cycle cost comparison: (1) the present time, (2) the time corresponding to maximum tolerable condition index, and (3) a time between those two.

The handbook method of life-cycle cost analysis is described in detail in the User's Handbook, Part II of this document. The computer method of life-cycle cost analysis is described in the following section.

6.2 Computer Method of Life-Cycle Cost Analysis

Equations 2.1 through 4.3 provide the technical and economic basis for solving for the optimal timing of the treatment, t*, for each protective or corrective strategy that is selected to be tested. This optimal timing of treatment will be the value of t* that yields the lowest discounted life-cycle cost, including both agency costs and user costs, for that strategy. An optimal time of treatment and its associated minimum life-cycle cost will be predicted for each strategy considered. The optimization procedure will provide the following information on each activity considered:

- The recommended timing of the activity, based on the minimization of life-cycle costs; and
- The total discounted agency and user costs for that activity if it is performed at the recommended time.

The optimization procedure is formulated in terms of the following objective function:

$$\begin{aligned} \text{Min } J \quad = \quad & \int U_2 \exp(-rt)\, dt \\ & + \quad C(S(t^*)) \exp(-rt^*) + U_1 \exp(-rt^*) \\ & + \quad (\exp(-rt^*)/(1-d_o^l))\{ \int [U_2+m] \exp(-rt)dt + \\ & + \quad C(S(l)) \exp(-rl) + U_1 \exp(-rl)\} \end{aligned} \qquad \text{(Eq. 6.1)}$$

where

- J = the total discounted life-cycle costs to be minimized for a given protective or corrective strategy
- r = discount rate
- d_o = the present worth factor $(1/(1+r))$
- l = the life computed for each subsequent deterioration and repair cycle following the initial one (Figure 6)
- m = periodic cost of maintaining the repair treatment (in this model only cathodic protection)

Other variables are as defined for Equations 2.1 through 4.3.

The total cost J is the sum of the costs in three periods of the analysis. The first integral expression (which applies from time t = 0 to t*) represents the discounted user costs prior to any treatment. (Routine maintenance costs for the deck could also be easily included here, if desired.) The expressions for $C(S(t^*))$ and U_1 represent the agency cost and the incremental user costs, respectively, during the construction period for the treatment. The expression in the braces represents the cost stream subsequent to the treatment, as illustrated in Figure 6. Equation 6.1 is easily solved using numerical methods.

6.3 Example Solutions of Optimal Deck Treatments

How the Solution Works

Interpreting of the figures below will be easier with an understanding of the numerical solution, a simple procedure. For a given treatment, the procedure steps through the analysis period year by year. Within each year, it performs the analysis described below.

- It simulates the application of the treatment in that year. For example, if the treatment is a concrete overlay, the computer simulates the performance of the overlay in Year 1. Next, it simulates the performance of the overlay in Year 2. It continues this procedure for each succeeding year in the analysis period.

- As each treatment is simulated, the procedure tallies all life-cycle costs (essentially the different terms in Equation 6.1), including both the agency and the user costs prior to the treatment, during the project to install the treatment, and after the treatment.

- The various cost components computed above are stored in a table organized by the year in which the selected treatment was simulated to be performed. At the end of the analysis (i.e., when costs have been tallied for all years within the analysis period), the optimal solution may be obtained by identifying the year with the lowest life-cycle costs associated with treatment performance.

It is very important to note that the time dimension is correlated with the condition of the bridge deck. Treatments that occur at the beginning of the analysis will affect the deck in its current condition. Treatments later in the analysis will affect a deck as it has deteriorated from its current condition to its condition at that later point in time.

Example Data

For this example, we assumed the following as constant for all the treatments:

- A relatively new, lightly distressed bridge deck with an area of 4,000 square feet (372 square meters) (four lanes wide totaling 48 feet (15 meters), with a length of about 83 feet (25 meters).

- An average daily traffic volume of 25,000, with a value of time of $10 per hour.

- A free-flow crossing time of 0.01894 minutes (based on the bridge length of 83 feet (25 meters) and a speed of 50 miles per hour (80 kilometers per hour).

- A normal two-way capacity of 96,000 vehicles per day and a capacity during the treatment of 57,600 vehicles per day (assuming one lane of the bridge is closed at a time).

- No annual maintenance either of the bridge deck before the treatment, or of any of the treatments after their installation.

- A discount rate of 5 percent.

The factors that varied in each of the cases were the characteristics of the treatments. Four basic types of protective or corrective strategies were considered in these examples:

- Patching (i.e., patching with portland cement concrete after removing deteriorated concrete).

- Applying a sealer after patching of deteriorated concrete.

- Applying a concrete overlay over the entire deck after patching deteriorated concrete.

- Installing of a cathodic protection system after patching deteriorated concrete.

Key values associated with these four options are shown in Table 2. Variations in these methods (to reflect different types of patches, sealers, overlays, cathodic protection systems, or other types of treatments) would be reflected by changing the values of the parameters in Table 2 (or other parameters in the model, such as the extent of bridge closure).

Example of Optimal Timing

An example of the computation of optimal treatment timing is given in Figure 10 for the concrete overlay. Figure 10 shows the life-cycle costs attributable to the simulated performance of the overlay treatment in each of Years 1 through 36 of the analysis period. Three cost curves are shown:

- Discounted agency costs attributable to performing the treatment, plus an amount for the presumed cycle of subsequent repairs (computed in lieu of a salvage value, as explained earlier).

- Discounted incremental user costs attributable to (1) riding on a badly deteriorated deck and (2) delays due to congestion during the treatment project. These costs are tallied not only surrounding the initial treatment (for which the optimal solution is being computed), but also for the series of subsequent repairs computed in lieu of a salvage value, as mentioned above.

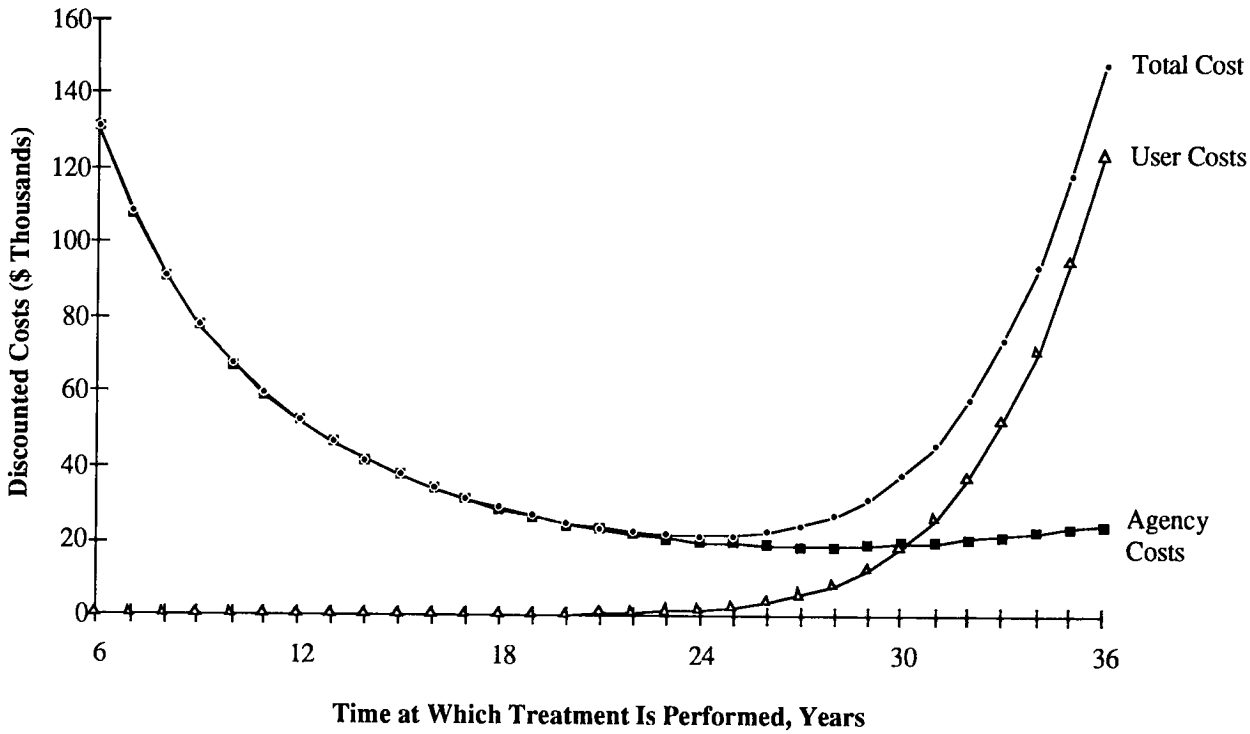
- Discounted total costs, representing the sum of the agency costs and the user costs.

The agency cost curve declines over time up to a point, because of the effect of the discount rate. A higher discount rate would result in a steeper decline over time, and a lower discount rate, a more gentle decline. At about 27 years, however, agency costs begin to increase, albeit in a very flat region of the curve. This increase occurs because the area of the deck requiring patching prior to overlay becomes excessive and starts to drive the costs of the treatment higher faster than the discount rate can compensate for the increase. Thus, the agency cost curve illustrates a tension in the solution between the rate of discount and the rate of deterioration of the bridge deck, and the opposing effects of these two parameters on costs.

Table 2. Input Data for Example Treatments

Parameter	Patching	Sealer	Concrete Overlay	Cathodic Protection
Service Life, years	6	10	20	30
Cost of Patching, dollars per square foot	35	35	35	35
Project Cost (to treat entire deck area), dollars	0	1,230	24,000	36,000
Productivity, square foot per day	135	135	135	135
Time for Project to Treat Entire Deck, days	0	4	10	20
Improvement Factor (fraction of condition improved)	0.765	0.765	0.765	1.0

Figure 10. Optimal Timing of Treatment (using concrete overlay as example)



The user cost is essentially 0 throughout the early part of the analysis, indicating very few incremental costs because the deck is new and has no adverse impacts on speed and travel time. Congestion costs due to the treatment project are negligible in all cases and for all years in this example, because of the relatively short length of the bridge and the modest level of traffic. This situation might change with longer spans, in which travel time effects would become more significant, or with detours around the bridge site. Implications of higher traffic volumes are investigated later in the example.

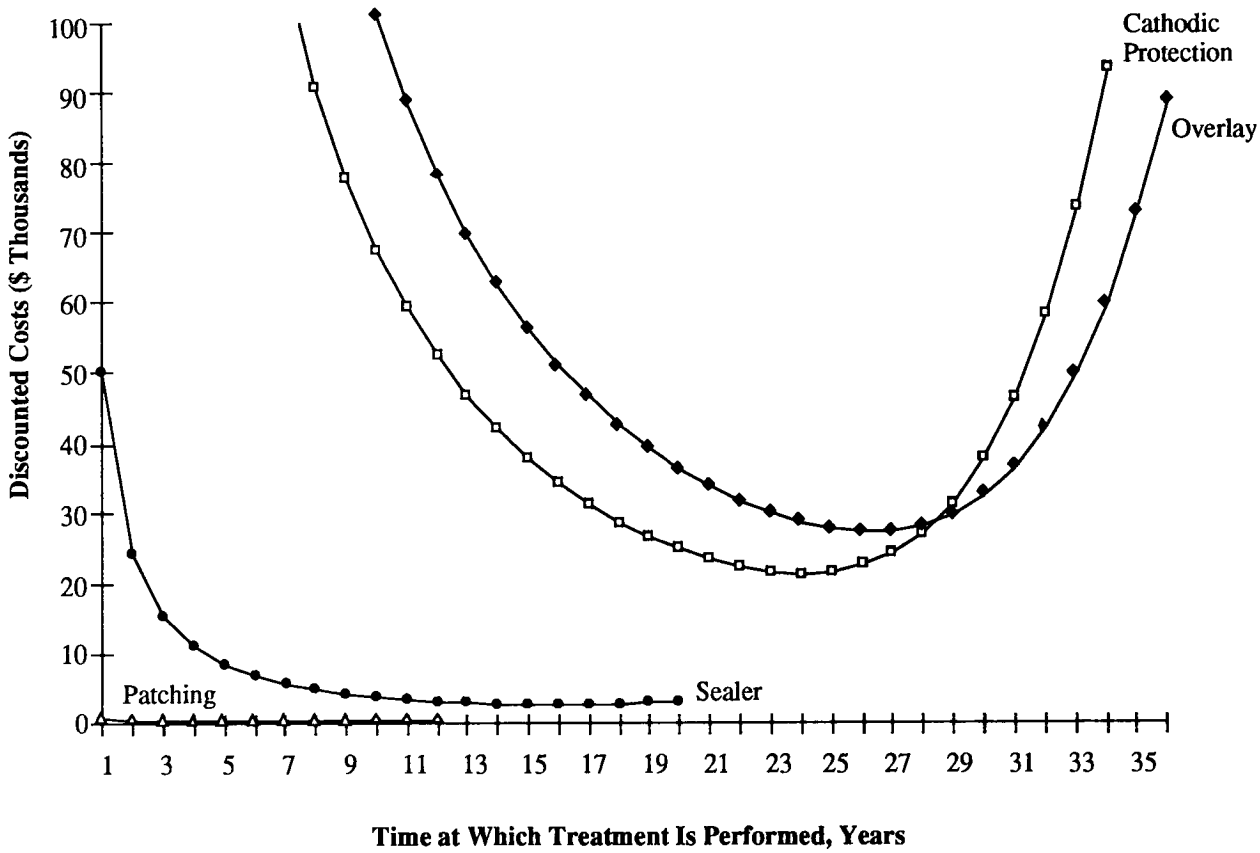
Note that the user costs do not begin to affect the result until the bridge deck condition deteriorates to a condition bad enough to have a noticeable effect on traffic. Furthermore, the increase in user costs may occur at relatively low values of the condition index, S, taken over the entire deck area, since distress is likely to be concentrated in the wheelpaths, exhibiting much higher "local" values of S. In effect, therefore, the incremental user costs act as an economic justification for bridge deck treatments. Viewed another way, the dramatically higher user costs attributable to worsening deck conditions are the penalties that drivers incur for deferred repair of a facility.

The optimal timing of the overlay treatment is obtained from the point of minimum total costs in Figure 10, which in this case is 24 years. This optimum is based on considering both agency costs and user costs. If user costs were not considered in this problem–that is, if the decision on overlay timing were predicated solely on agency costs–the optimal timing would have been determined to be later, in Year 27. More important, the region of optimal timing is more clearly defined when user costs are considered. Considering only agency costs, the least-cost value occurs in a very flat part of the curve, where the costs of deferral may not be significant enough to justify expenditures against competing bridge needs. In other words, considering agency costs alone does not introduce the full scope of the benefits of bridge treatments, or the full scope of penalties if such treatments are deferred or foregone.

Comparison of Treatments

Analyses such as those described above for overlays were performed for all four treatments listed in Table 2. The results are summarized in Figure 11, showing only the total cost curves for each treatment. Bear in mind that these results are for the relatively new (and therefore only slightly distressed) bridge deck that was considered in the example. In this light, the results are interpreted as follows:

Figure 11. Comparison of Treatments



- The optimal time for patching occurs strictly in Year 5, although the total cost curve is so flat that the activity would be justified virtually at any time required in the first 10 or 15 years. Costs are low, of course, because the deck is relatively undamaged, so the total costs of the treatment are small, even though the unit costs (per square foot of distressed deck area) are relatively high compared to those of the other treatments.

- The optimal time for sealer application occurs strictly in Year 16, although total discounted costs do not vary significantly within 5 years before or after this time. Total discounted costs in this region are somewhat more than for concrete patching, but still relatively low.

- Both concrete overlays and cathodic protection have optimal times much later in the deck's life, and at higher costs than for either the sealer or patching. For overlays the optimal treatment time is 24 years, as discussed earlier; for cathodic protection it is 26 years. (These treatments may show greater benefits in future versions of the model as more sophisticated corrosion relationships are included for protection techniques and better data on service life and degree of improvement are developed through other SHRP projects.[4])

These results indicate the value of preventive and relatively small-scale corrective activities at this point of the deck's life cycle. Since the current level of distress is small, treatments that can correct this distress or prevent further distress at relatively low cost are preferred.

Effect of Parameter Variation

The parameters identified in Table 2 can be varied to assess their impact on the solution. To give one example, we investigated the effect of an increased traffic volume. The average daily traffic of 25,000 in Table 2 was increased to 55,000 (just below the bridge capacity during the treatment project). Results and comparison with the original case are shown in Figure 12, using the overlay treatment as an example.

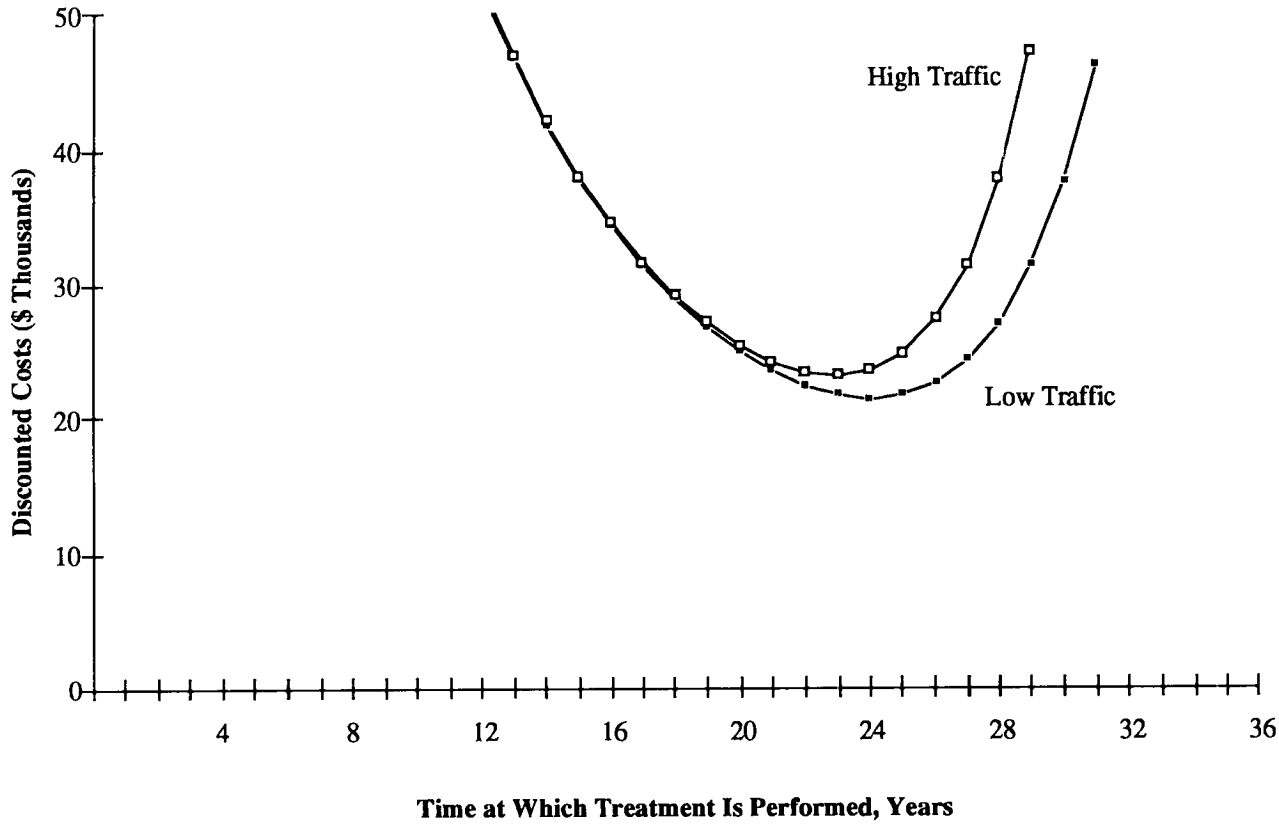
The increase in traffic results in an earlier optimal time of treatment (from 24 to 23 years) and a somewhat higher minimum total cost. Both of these effects are expected and consistent with the problem formulation. A higher traffic volume increases the penalties of a deck in bad condition (since more users experience this condition), prompting an earlier treatment. The higher total costs are associated with several effects:

- The earlier performance of the treatment, which means that the agency costs are not discounted as much.

- The greater number of users experiencing a deteriorating deck condition.

- Interactions among users themselves: that is if traffic speed is reduced somewhat because of distress in the wheelpaths on the deck, the greater number of users increases the degree of congestion exponentially.

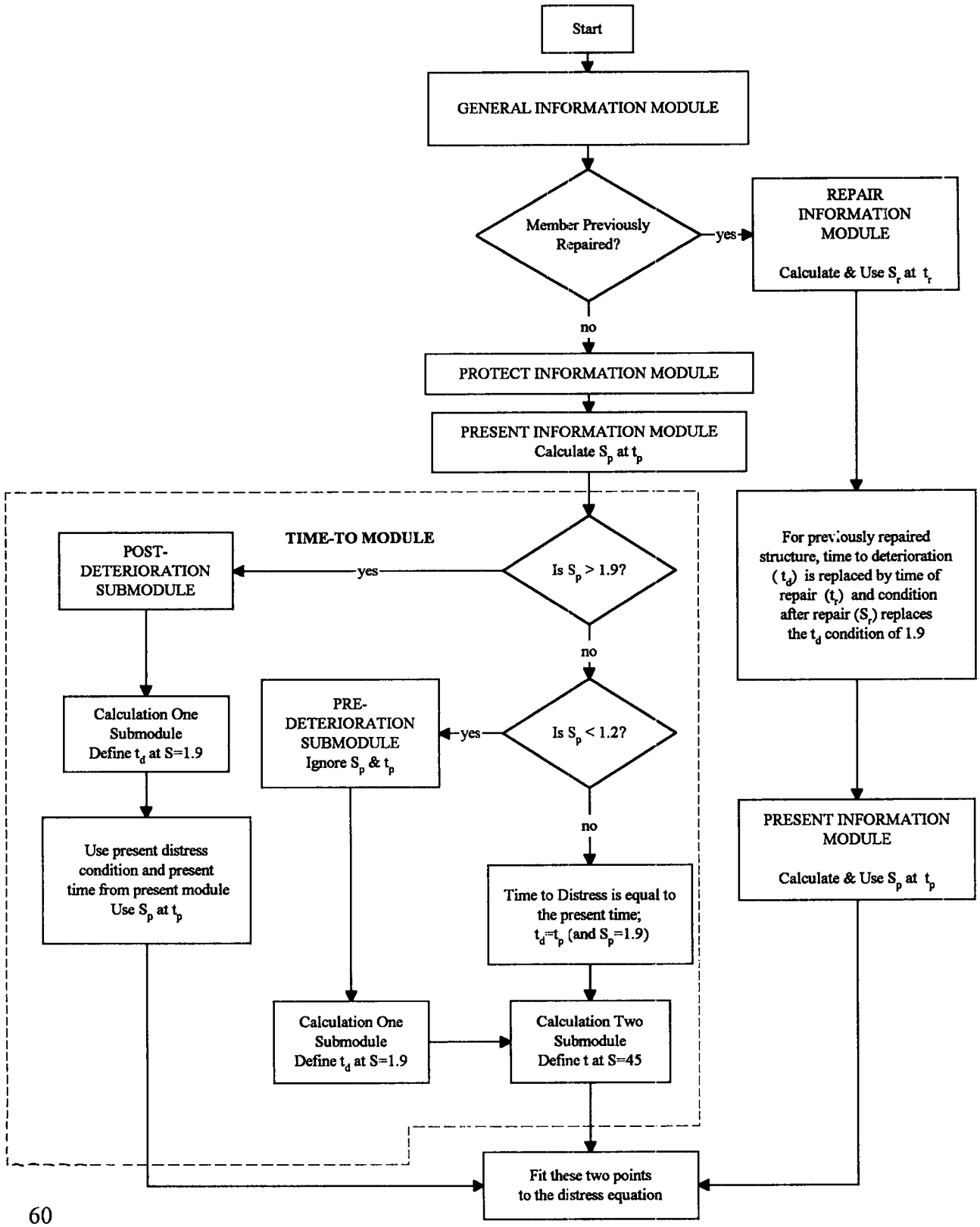
Figure 12. Difference of Traffic (using overlay as example)



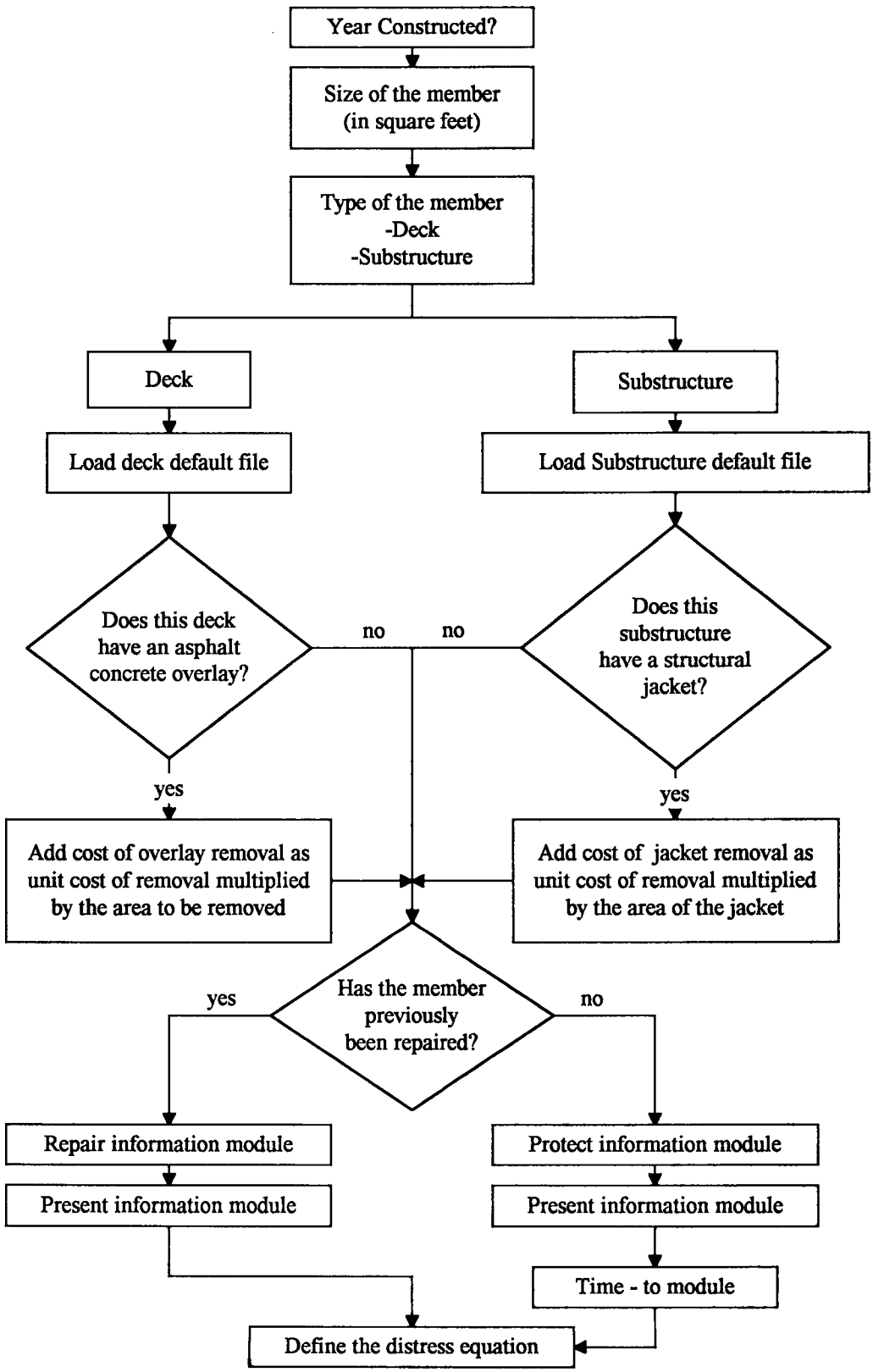
Appendix A

Flowcharts

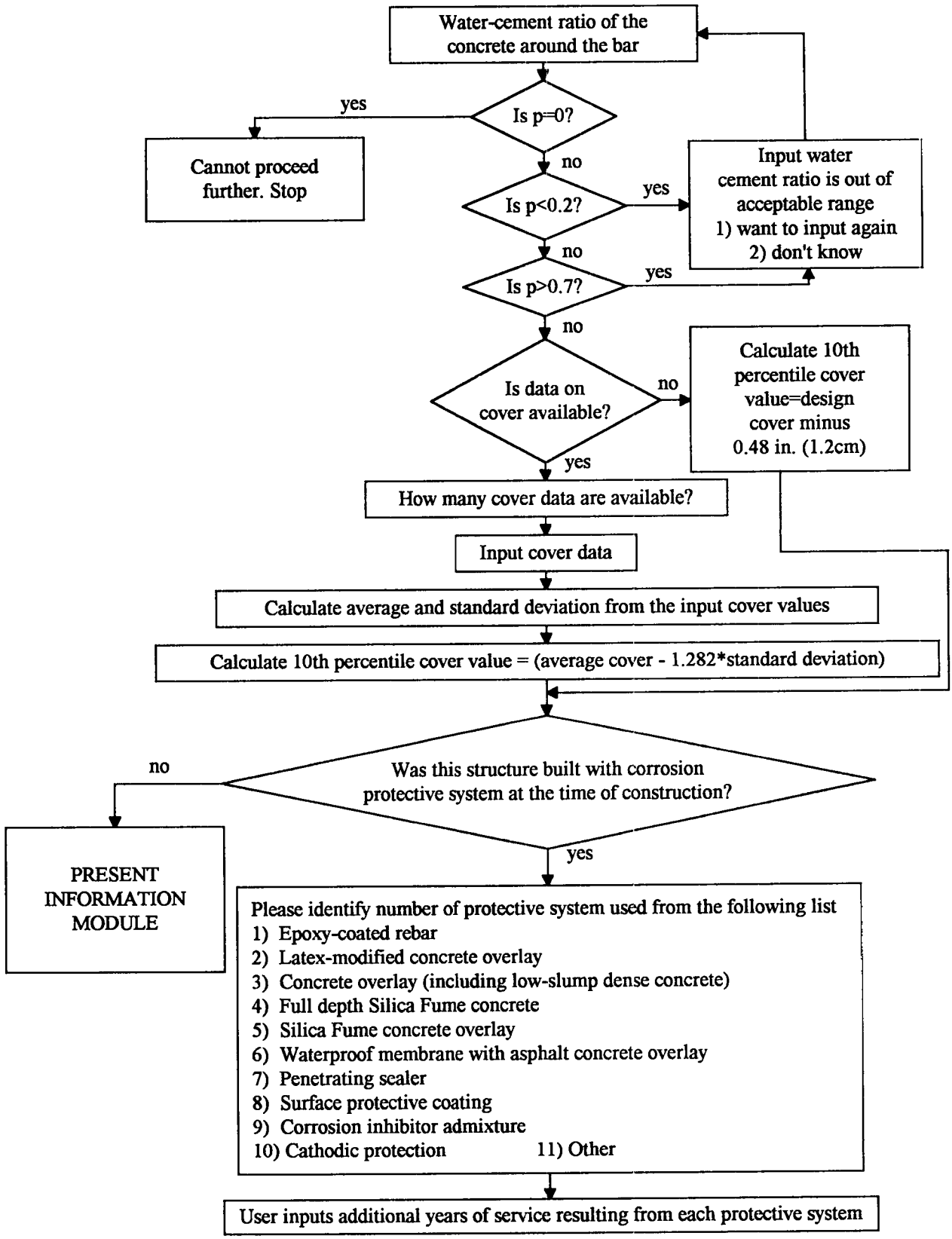
Flowchart 1. General Technical Methodology for Technical Goal One



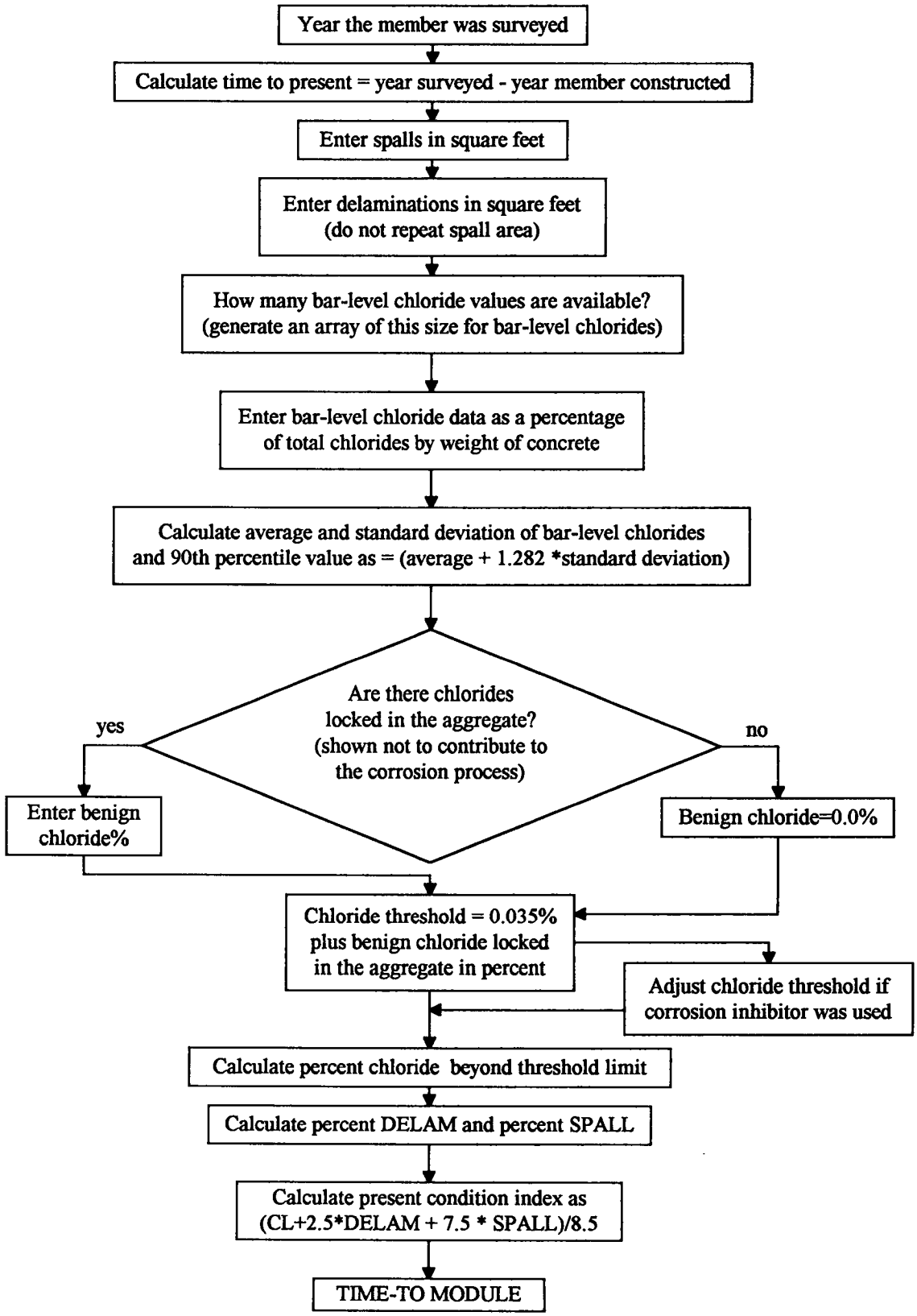
Flowchart 2. General Information Module



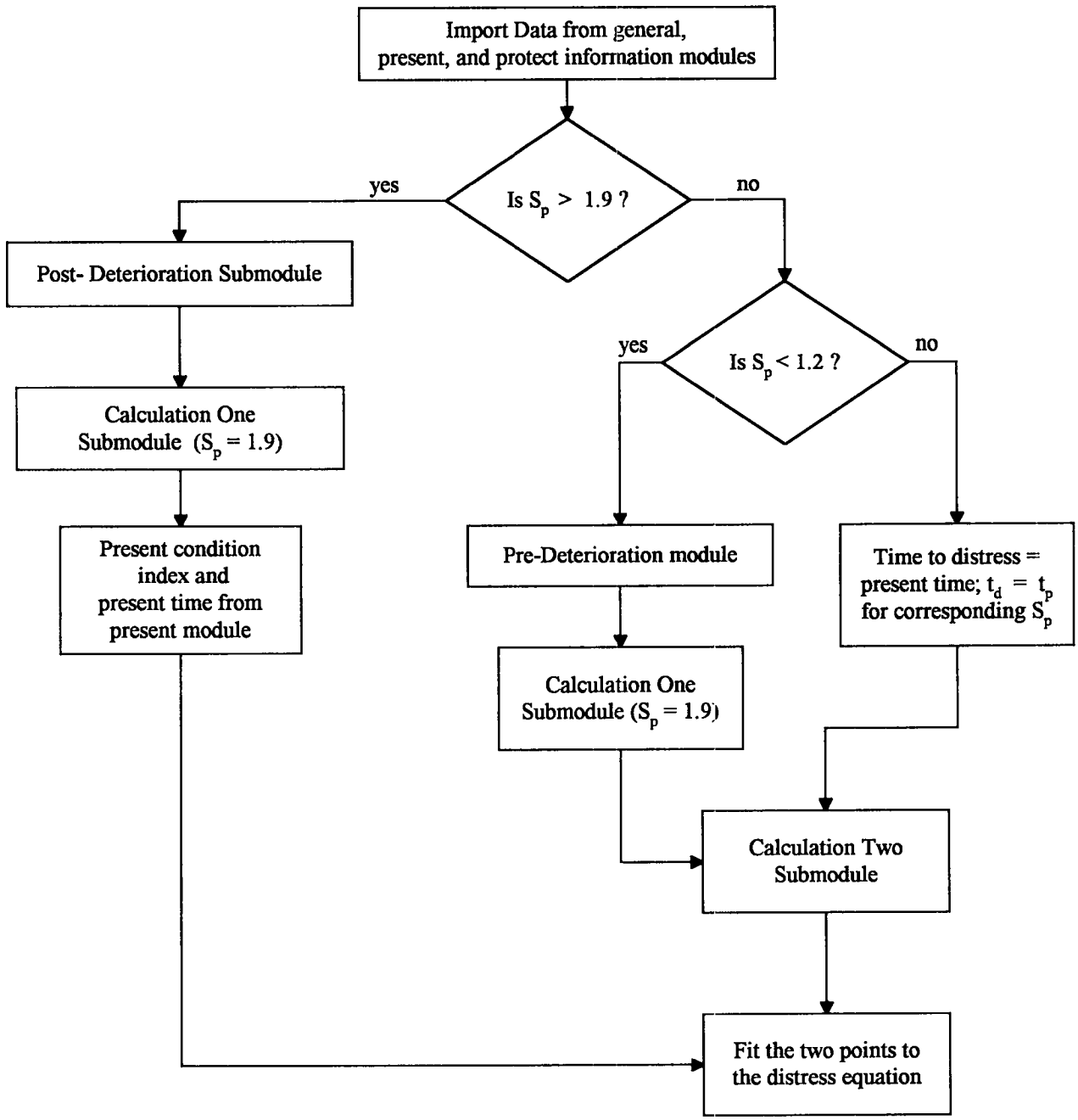
Flowchart 3. Protect Information Module



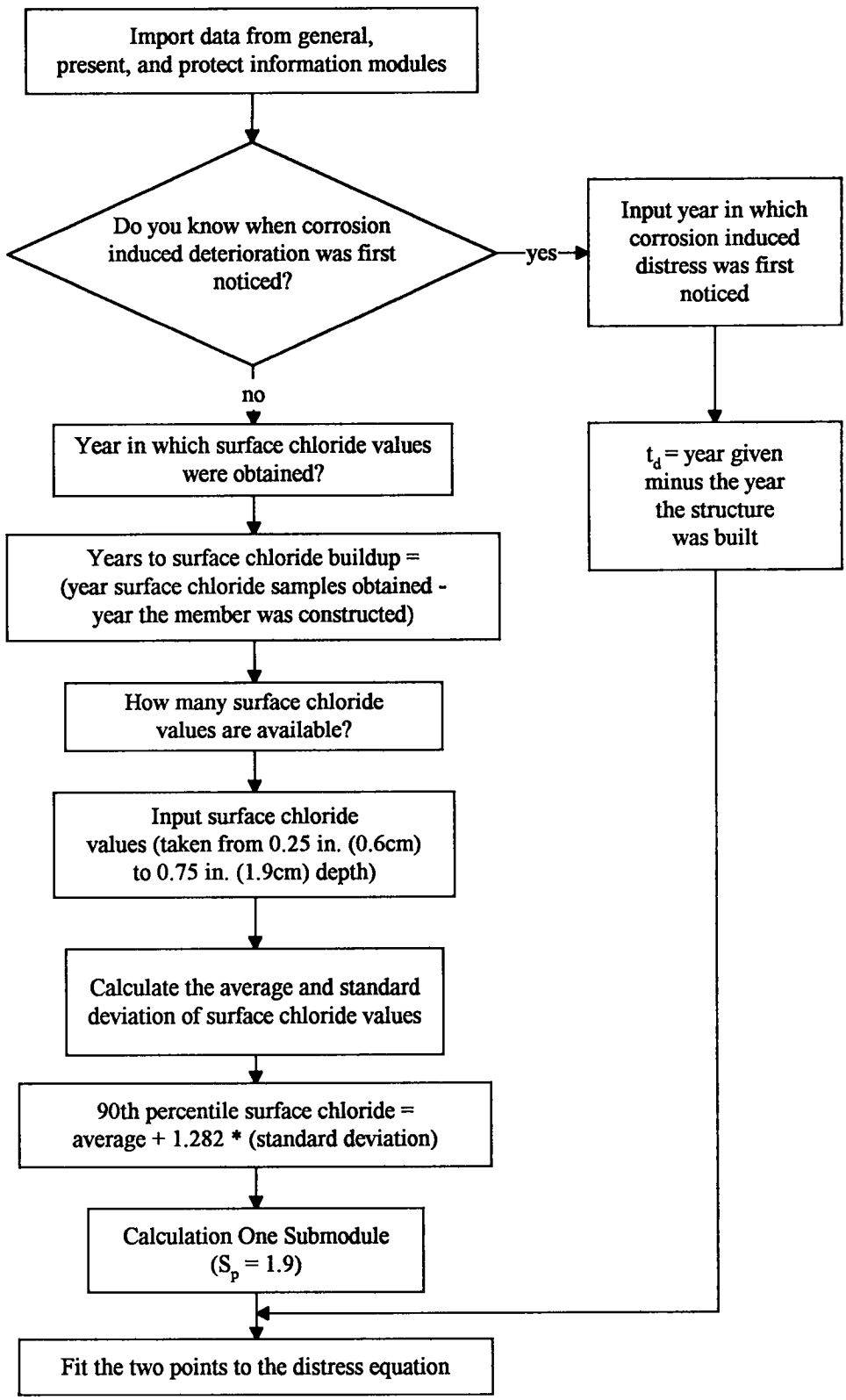
Flowchart 4. Present Information Module



Flowchart 5. Time-to Module



Flowchart 6. Post-Deterioration Submodule



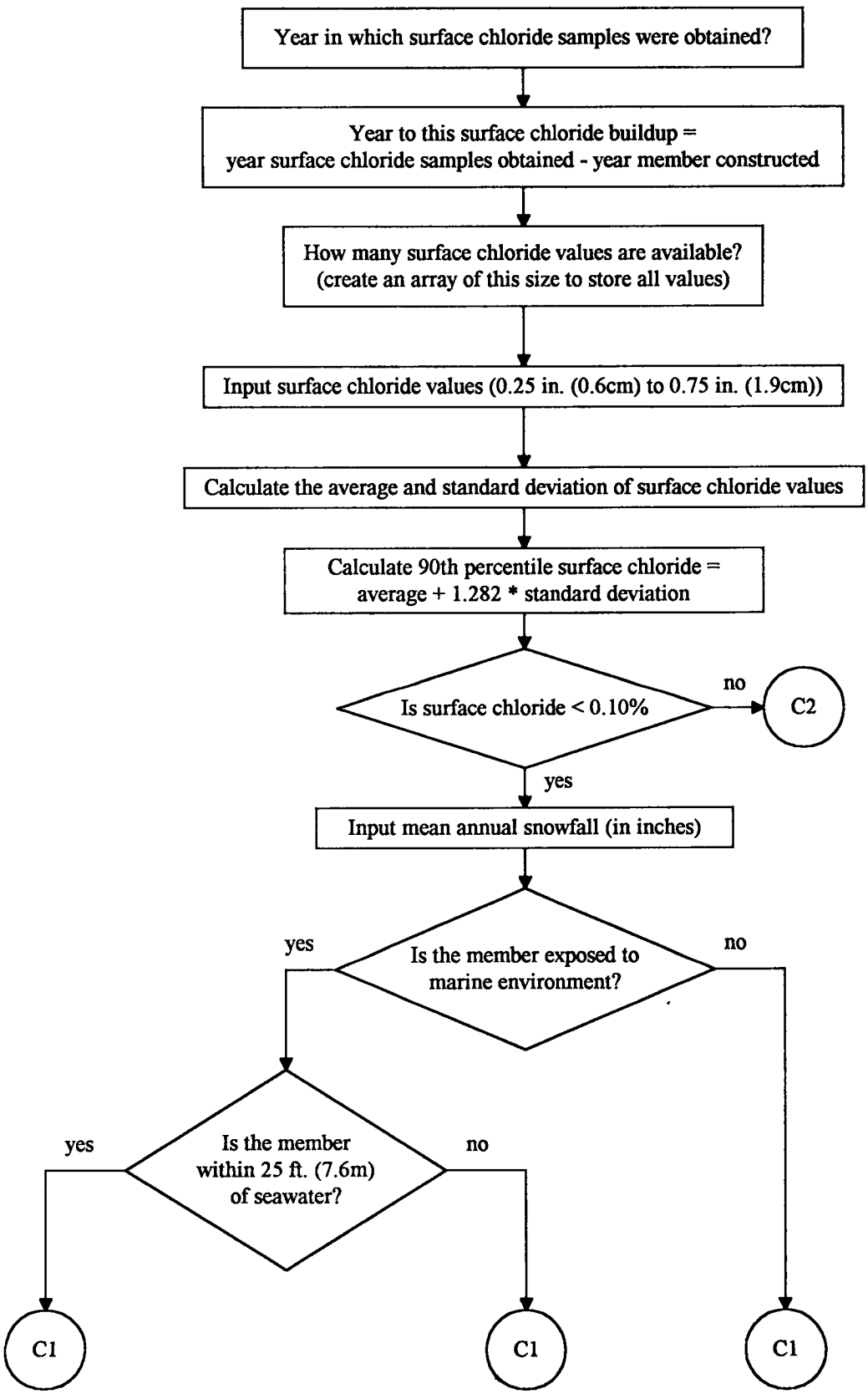
Flowchart 7. Calculation One Submodule

This module calculates the time to first deterioration, t_d, using the following formula

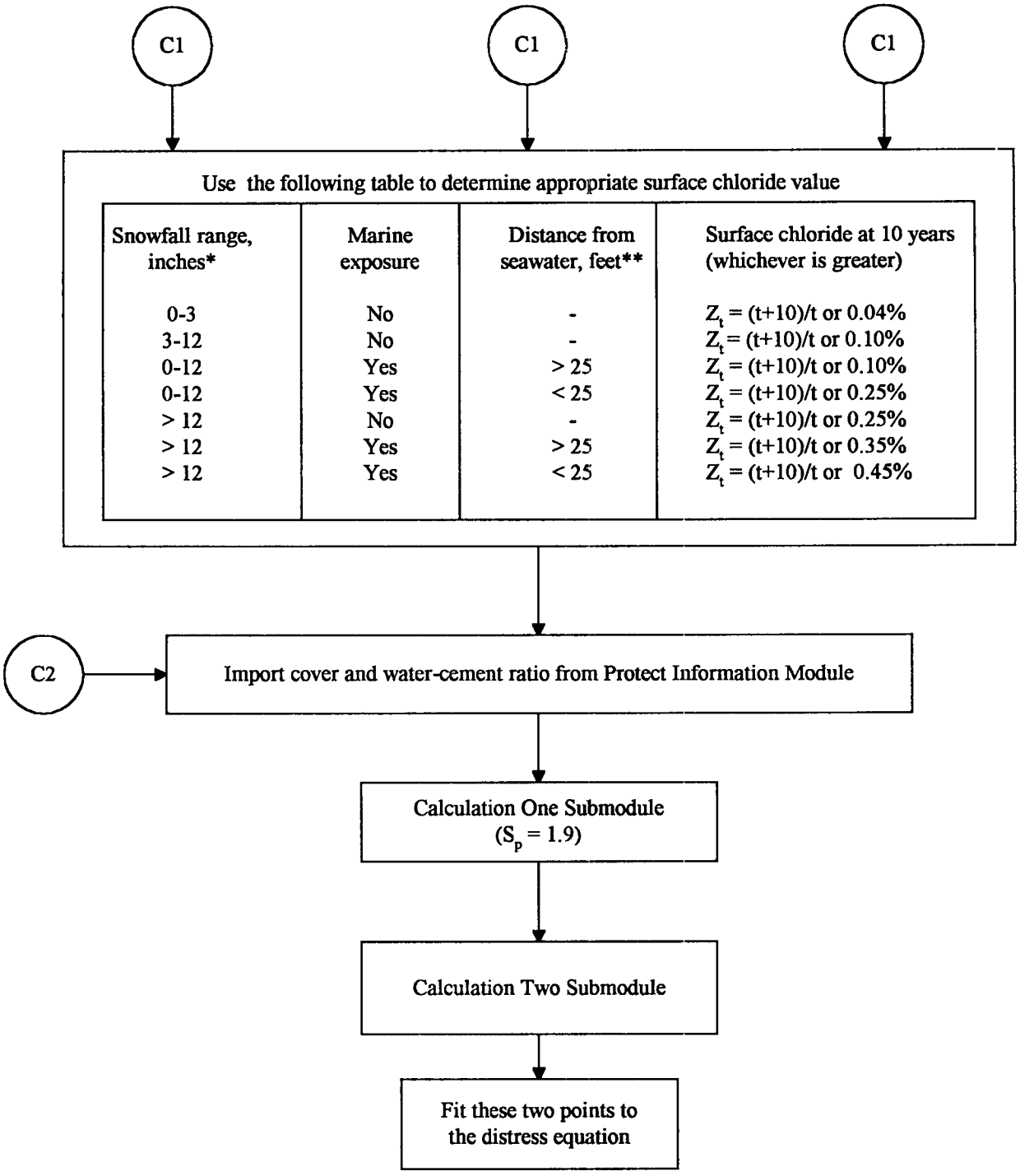
$$t_d = \left[\frac{2.695\, d^{1.22} t^{0.21}}{Z_t^{0.42} P} \right]^{\frac{1}{1.21}}$$

Where
t_d = time to first signs of corrosion-induced distress, years
d = depth of bar cover, inches
Z_t = surface chloride concentration, percent by weight of concrete
t = age at which Z_t was measured, years; and
P = concrete water-cement ratio

Flowchart 8. Pre-Deterioration Submodule



Flowchart 8. Pre-Deterioration Submodule (continued)



* 1 inch is 2.54 centimeters

** 1 foot is 0.305 meters

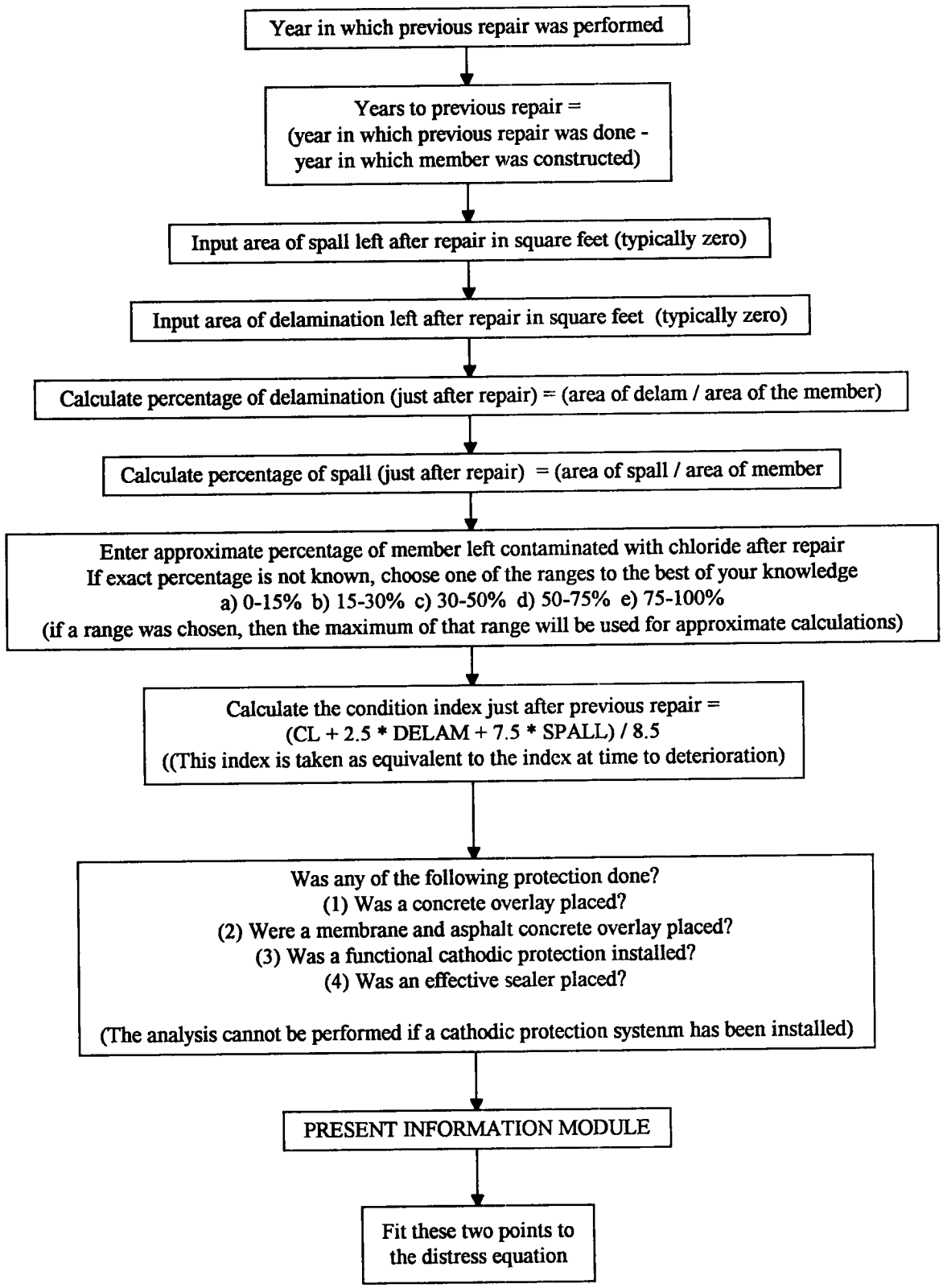
Flowchart 9. Calculation Two Submodule

This module is required to estimate the condition at some time in the future after the time to deterioration, by adjusting the slope of the distress curve. The rate of distress will be dictated by many factors, including the steel concentration, oxygen availability, and the resistivity of the concrete in the field. All these factors are not known. However, an estimate of whether the deterioration rate will be low, medium, or high is possible, and standard curves can be assigned to each rate designation. This can be based on the wet resistivity of the concrete, per a suggested test method in Appendix E.

Distress Rate	Resistivity ohm-cm	Years to Condition Index of 45
High	<7,500	t_d+10
Medium	7,500 to 30,000	t_d+20
Low	>30,000	t_d+35

From the appropriate curve, the time (t) to reach S=45 can be defined and output to the cost analysis in lieu of S_p and t_p. Actual adjustments to the deterioration curve will need to be defined.

Flowchart 10. Repair Information Module



Appendix B

Report Format Example

Condition Index Versus Time—Before Treatment
Sample Computer Run

Please enter the current year (all four digits) ? 1992

Year the member was constructed (all four digits) ? 1977

Size of the member (in square feet) ? 4000 (372 square meters)

Type of the member :

1 - Deck
2 - Substructure

Input type of member: ? 1

Does this deck have an Asphaltic Concrete Overlay (Y/N) ? n

Has this member been rehabilitated previously (Y/N) ? n

This is Protect Information Module

Please enter water-cement ratio of the concrete around the bar ? 0.5

How many cover data are available ? 40

Please enter cover values in inches:

1 ? 1.4 (3.6 centimeters)
2 ? 1.9 (4.8 centimeters)
.
.
40 ? 0.9 (2.3 centimeters)

Was this structure built with corrosion protective system at the time of construction ? n

This is Present Information Module

Please enter the year the member was surveyed ? 1992

Please enter the total spall area in square feet ? 240 (22 square meters)

Please enter the total delaminated area in square feet ? 720 (67 square meters)

How many bar level chloride values are available ? 10

Please enter chloride values as percent by weight of concrete :

1 ? 0.0230
2 ? 0.0179
.
.
10 ? 0.1229

Are there chlorides locked in the aggregate (shown not to contribute to the corrosion process) (Y/N) ? n

This is Time - To Module

This is Post - Deterioration Submodule

Do you know when (i.e., at what year) corrosion induced deterioration was first noticed ? n

Please enter the year the surface chloride values were obtained : 1992

How many surface chloride values are available ? 10

Please enter surface chloride values as percent by weight of concrete :

1 ? 0.3423
2 ? 0.3678
.
.
10 ? 0.4115

The Condition Parameters are :

Condition Index at Time to First Deterioration: $S_d = 1.9$

Concrete Age at First Deterioration: $t_d = 6.7$ years

Condition Index at Present: $S_p = 20$

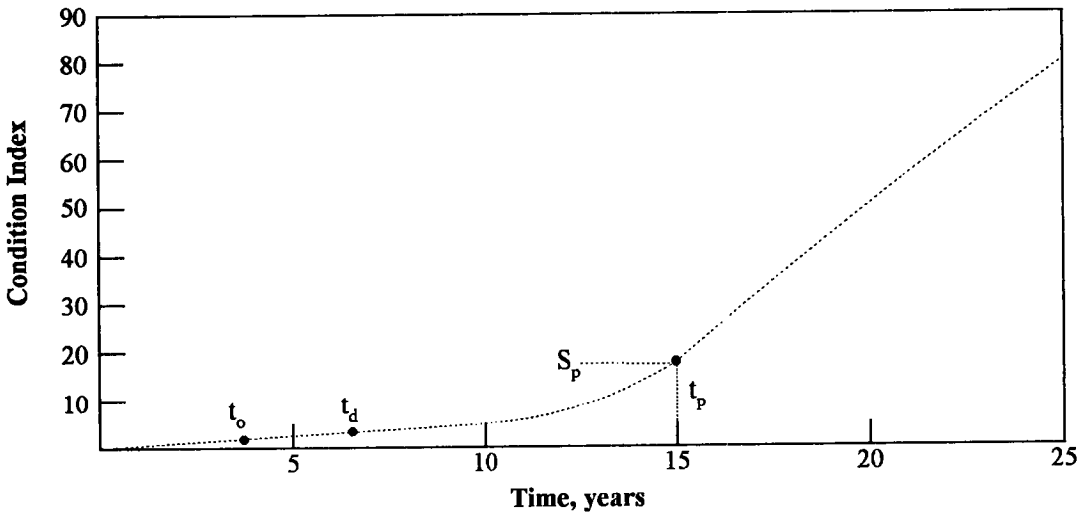
Present Age of the Concrete: t_p = 15 years

Deck Area = 4000 square feet (372 square meters)

Constants of the Distress equation are:

A1 = 407.2 B1 = -0.3082

Condition Index by Predictive Model



For this example:
Condition Index S_t = 100 / (1+407.2 (exp(-0.3082 x years)))

Note:
No protective system used. Not previously rehabilitated. Constructed in 1977. Field evaluated in 1992.
Water-Cement Ratio = 0.5 Spalls = 6%
Surface Chloride (90th Percentile Value) = 0.4247% Delaminations = 18%
Cover over bar (10th Percentile Value) = 0.774 in. Deck Area Contaminated by Chloride = 80%

Appendix C

Condition Index

Condition Index (S)

Three major factors influence the corrosion condition of the structure at a given time.

- Percent bar-level chloride contamination (CL).
- Percent delamination (DELAM).
- Percent spalling (SPALL).

Of these, spalling is the most important, delamination is second, and the bar-level chloride contamination is the least important when considering treatment at a given time.

The importance of each of these variables (in triggering treatment) was defined as follows:

- Spalling is three times more important than delamination.
- Delamination is 2.5 times more important than bar level chloride contamination.

$$S = \frac{CL+2.5(DELAM)+7.5(SPALL)}{8.5}$$

where

CL	=	percent of bar-level samples with chlorides higher than the corrosion threshold value
DELAM	=	percent of area with nonvisible undersurface fractures only
SPALL	=	percent of area with visible deterioration
8.5	=	a normalizing factor

Evaluate ten bar-level chloride samples per member or per 5000 square feet (465 square meters), whichever results in the greater number of data points. Sampling depth shall be between the cover depth and cover depth plus 0.5 inches (1.27 centimeters) at each location.

Determine whether or not each value is greater than or equal to or less than the threshold for corrosion by weight of concrete (0.035 percent (350 ppm), plus any chloride locked in the aggregate, plus any corrosion inhibitor effect). Calculate the percentage of samples greater than or equal to the threshold. This will be the percentage of the structure which is chloride contaminated.

The percentages of spalling and delamination are determined by surveying and mapping the entire surface of the structure. Sample Index values for various conditions are given in the following table.

SPALL	DELAM	CL	Index
0	0	100	12
0	100	100	41
0	80	100	35
20	50	100	44
15	40	100	37
10	20	60	22
0	10	40	8
0	1	50	6
0	0	25	3
0	2	25	4

Appendix D

Time to Deterioration

Time to Deterioration

Stratfull[6,7] defined the following formula for time to deterioration (corrosion-induced distress):

$$R_t = \frac{10^{0.0442C_o}\, C_o^{0.717} Si^{1.22}\, 1011}{K_o^{0.42}\, W_m^{1.17}}$$

where

R_t	=	years to deterioration of concrete exposed to saline water (expressed as t_d in this report)
C_o	=	sacks of cement per cubic yard of concrete
Si	=	depth of steel below the surface in inches
K_o	=	chloride concentration of water, parts per million
W_m	=	mixing water in percent of concrete volume

Clear[1] (1975) showed that the following modified Stratfull formula yielded similar results:

$$R_t = \frac{129\, d^{1.22}}{K^{0.42}\, P}$$

where

d	=	depth of bar cover, inches
K_o	=	surface chloride concentration (parts per million)
P	=	water-cement ratio
R_t	=	time to first signs of corrosion-induced deterioration (expressed as t_d in this report)

The above formula applies mainly to sea water situations. It can be modified to include all chloride environments. If the accumulation of surface chloride is assumed to be proportional to the square root of time then:

$$Z_t = z\sqrt{t} \qquad \text{or} \qquad z = \frac{Z_t}{\sqrt{t}}$$

Where Z_t is the surface chloride as a percentage by weight of concrete at time "t" during the life of the structure.

For R_t years of life

$$Z_R = \left[\frac{Z_t}{\sqrt{t}}\right] R_t^{0.5}$$

Where Z_R is the surface chloride at time to deterioration (R_t in years).

$$K_o = Z_R \times 104$$

therefore

$$K_o = \left[\frac{Z_t}{\sqrt{t}}\right] R_t^{0.5} \times 10^4$$

Substituting this value of K_o in Clear's formula

$$R_t = \frac{129\ d^{1.22}}{\left[\left[\frac{Z_t}{\sqrt{t}}\right] R_t^{0.5} \times 10^4\right]^{0.42} P} \qquad \text{or} \qquad R_t = \left[\frac{2.695\ d^{1.22}\ t^{0.21}}{Z_t^{0.42}\ P}\right]^{\frac{1}{1.21}}$$

where

d = depth of bar cover, inches
P = water-cement ratio

Z_t = surface chloride concentration, percent by weight of concrete
t = age at which Z_t was measured, years

This formula will be used to calculate R_t (expressed as t_d in this report), except in special situations.

Condition index (S) at time to deterioration (t_d) is defined as follows:

Bar-level chloride contamination = 15 percent

Delamination = 0.5 percent

Spalling = 0 percent

Condition index at t_d = S_d = 1.9

Time to Corrosion Initiation, t_0

If $t_d > 20$ years, $t_o = t_d - 5$
If $t_d = 10$ to 20 years, $t_o = t_d - 3.5$
If $t_d < 10$ years, $t_o = t_d - 2$

Condition index at t_o = S_o = 1.2
(10 percent chloride contamination, 0 percent delamination, and 0 percent spalling)

Appendix E

Calculation Two Submodule

Calculation Two Submodule

Average Wet Resistivity, ohm - cm**	Years to Condition Index of 45 percent	Distress Rate* (percent index increase per year)
< 7,500	t_d + 10	4.31
7,500 to 30,000	t_d + 20	2.16
>30,000	t_d + 35	1.23

* Distress Rate (percent index increase per year) is calculated as follows:

$$\frac{\text{Condition Index} - 1.9}{\text{Years to Condition Index} - t_d}$$

For example the distress rate for medium resistivity concrete is:

$$\frac{(45 - 1.9)}{(t_d + 20 - t_d)} = \frac{43.1}{20} = 2.16$$

**ESTIMATED ELECTRICAL RESISTIVITY OF CONCRETE MATERIALS

Obtain three fully cured core or cylinder samples at least 4 inches (10.2 centimeters) in diameter and 2 inches (5.1 centimeters) long. The samples shall be completely representative of the concrete to be studied.

Perform Rapid Permeability tests on each of the three samples in accordance with the procedure of AASHTO T277-83I "Rapid Determination of the Chloride Permeability of Concrete", except add the following:

Immediately prior to connection of the 60-volt power supply leads, record the two pin AC resistance between the two cell halfs, measured with a Nilsson 400 or equivalent.

Calculate estimated resistivity by multiplying the measured AC resistance by 16.8.

Report the estimated resistivity (73 degrees F, vacuum saturated) for each specimen. Average the findings for the three individual specimens and also report the average and the range.

Calculation Two Submodule

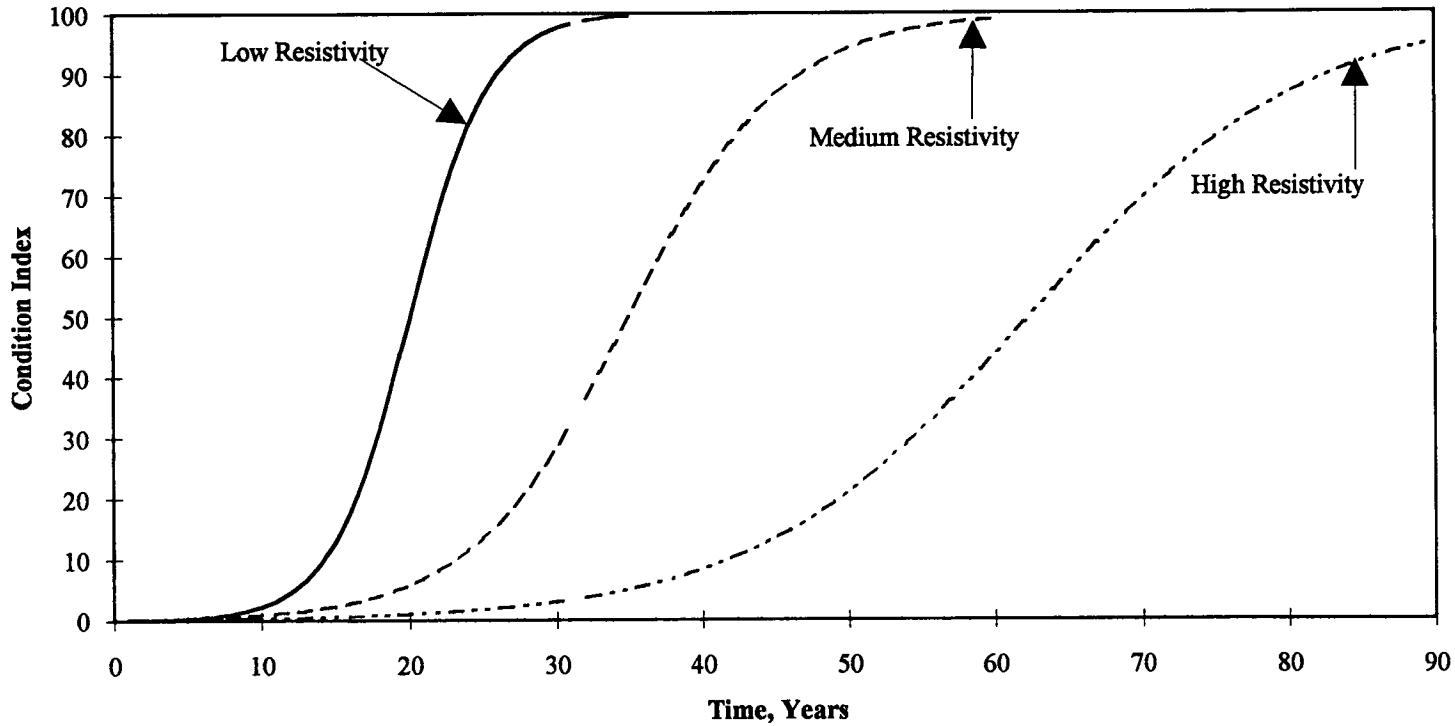
Example of Years to Condition Index of 45 for Concretes of Different Permeabilities

Age years	Cover 10th Percentile	Surf. level CL, %	RPT Coulombs	W/C ratio	Time to Det., t_d	Time to Cond. 45	Constants A	Constants B	Comments
15	1.4	0.3850	3800	0.45	13.73	33.73	675	0.1862	Moderate resistivity
25	1.4	0.7700	3800	0.45	11.80	31.80			
5	1.4	0.2000	3800	0.45	14.25	34.25			
15	1.4	0.2000	500	0.28	25.52	60.52	793	0.1070	High resistivity
25	1.4	0.3500	500	0.28	22.96	57.96			
5	1.4	0.1000	500	0.28	26.82	61.82			
15	1.4	0.5500	6500	0.60	9.57	19.57	1858	0.3744	Low resistivity
25	1.4	1.0500	6500	0.60	8.35	18.35			
5	1.4	0.2500	6500	0.60	10.39	20.39			

Note : Surface Chloride levels are estimated for the various ages based on experience

Calculation Two Submodule

Condition Curve for Concretes of Different Permeabilities



Appendix F

Criteria for Preventive Maintenance

Criteria for Preventive Maintenance

Problem

Let us consider a structure (for example, a bridge deck) constructed 5 years ago with 0.15 percent surface chloride (measured at between 0.25 and 0.75 inches (0.6 to 1.9 centimeters) from the surface). The bar-level chloride is below the threshold at present. Is it feasible to apply a sealer, membrane, or overlay to prevent corrosion? If so, how many times can we apply this kind of protective system (as a preventive maintenance) before the 0.15 percent surface chloride causes the bar-level chlorides to exceed the threshold.

Procedure to Determine the Applicability of a Protective System with 100% Effectiveness

Example #1

Age at present, t	=	5 years
Cover (10th percentile value), d	=	1.4 inches (3.6 centimeters)
Water-cement ratio	=	0.28
Surface chloride at present, Z_t	=	0.15 percent
Effectiveness of the protective system	=	100 percent

Let us assume that this structure is protected from further intrusion of chlorides, and hence the surface chloride remains constant at 0.15 percent. Though the bar-level chloride at present is less than the chloride threshold value, the existing surface chloride will diffuse through with time and may eventually increase the bar-level chloride to the threshold and beyond. Once the bar-level chlorides reach the threshold, protective systems such as sealers, membranes, and overlays may not be effective in arresting corrosion. Hence it is necessary to determine the time to corrosion (when bar-level chlorides reach threshold) due to 0.15 percent of surface chloride.

Stratfull developed an equation to determine the time to deterioration for constant surface chloride and was later simplified by Clear. The simplified formula by Clear is given below:

$$t_d = \frac{129\ d^{1.22}}{K_o^{0.42}\ P}$$

where

K_o	=	surface chloride in parts per million
d	=	cover in inches (10th percentile value)
P	=	water-cement ratio equivalent to RPT coulombs
t_d	=	time to deterioration in years (first signs of delaminations, cracks, or rust stains)

Surface chloride Z_t, as a percent by weight of concrete, can be expressed in ppm as

$$K_o = Z_t * 10000$$

Substituting this in the above equation yields

$$t_d = \frac{2.695\ d^{1.22}}{Z_t^{0.42}\ P}$$

We also know that t_o (time to corrosion) can be calculated from t_d as follows:

$$t_o = t_d - 2 - \frac{3}{1+125\ e^{-0.3219 t_d}}$$

For the above data:

t_d = 32.2 years and t_o = 27.2 years

Hence, the remaining time to corrosion = 27.2 - 5 = 22.2 years

If the protective system considered has 10 years of life, then it can be applied twice before rehabilitation. However, if the protective system has 20 years of life, it can be applied only once before rehabilitation.

Example #2

Age at present, t	=	5 years
Cover (10th percentile value), d	=	1.4 inches (3.6 centimeters)
Representative water-cement ratio (equivalent to RPT value), P	=	0.45
Surface chloride at present, Z_t	=	0.20 percent
Effectiveness of the protective system	=	100 percent

t_d = 17.8 years and t_o = 13.7 years

Hence the remaining time to corrosion = 13.7 - 5 = 8.7 years

Procedure to Determine the Applicability of a Protective System with less than 100 percent Effectiveness

In both the examples analyzed above, the surface chloride was assumed to remain constant after the protective system (as a preventive maintenance) was applied. But in reality there is always a small seepage of chloride through the protective system, depending on the effectiveness of the protective system. For example if the protective system is said to be 90 percent effective, then it allows only 10 percent of the previous year's increase in surface chloride value per year every year once the protective system is set in place.

Example #3

Age at present, t	=	5 years
Cover (10th percentile value), d	=	1.4 inches (3.6 centimeters)
Representative water-cement ratio (equivalent to RPT value), P	=	0.28
Surface chloride at present, Z_t	=	0.15 percent
Effectiveness of the protective system	=	90 percent

The surface is protected with 90 percent effective system (i.e., the surface chloride increases by 10 percent every year).

Z_t = 0.15 percent at 5 years after construction
Z_t at the sixth year after construction

$$= 0.15 + \left[0.15 - \frac{0.15\sqrt{5-1}}{\sqrt{5}}\right] 0.10$$

Similarly Z_t at time to deterioration

$$= 0.15 + \left[0.15 - \frac{0.15\sqrt{5-1}}{\sqrt{5}}\right] 0.10\ (t_d - t)$$

or in general terms

$$= Z_t + \left[Z_t - \frac{Z_t\sqrt{t-1}}{\sqrt{t}}\right] e\ (t_d - t)$$

where e = (100 - effectiveness in percent)/100

Surface chloride in parts per million:

$$K = \left(Z_t + \left[Z_t - \frac{Z_t\sqrt{t-1}}{\sqrt{t}}\right] e\ (t_d - t)\right) * 10000$$

Substituting this surface chloride expression in Clear's formula yielded:

$$t_d = \frac{2.695\ d^{1.22}}{Z_t^{0.42}\ P\left[1 + \frac{(t_d - t)\ e\ (\sqrt{t} - \sqrt{t-1})}{\sqrt{t}}\right]^{0.42}}$$

Using the data above

$t_d =$ 31 years and $t_o = 26$ years

Hence, the remaining time to corrosion = 26 - 5 = 21 years.

Example #4

Age at present, t	=	5 years
Cover (10th percentile value), d	=	1.4 inches (3.6 centimeters)
Representative water-cement ratio (equivalent to RPT value), P	=	0.45
Surface chloride at present, Z_t	=	0.20 percent
Effectiveness of the protective system	=	90 percent

Using the data above data,

t_d = 17 years and t_o = 13 years

Hence, the remaining time to corrosion = 13 - 5 = 8 years.

Comments:

The variable effectiveness formula is slightly more accurate. However, since all protective systems in consideration should be 90 percent or more effective, we believe that procedure #1 (assuming 100 percent effectiveness) is an adequate approximation. Remember, however, that the life of a preventive maintenance overlay is the time it completely blocks chloride intrusion into the base concrete (and not its physical life).

PART II—HANDBOOK

1. Introduction

1.1 Purpose

In order to minimize the cost of repairing or replacing of deteriorating concrete bridges at the network level, it is essential that cost-effective actions be taken at the project level. This handbook provides a systematic methodology to guide technical personnel of highway agencies in determining rational, cost-effective strategies for treating specific concrete bridge components. The output from the methodology answers the user's questions regarding the type and timing of treatment to achieve the lowest life-cycle cost.

1.2 Approach

The methodology takes the following factors into account in conducting life-cycle cost analysis:

1. The condition of the concrete component and its performance,

2. The technical compatibility, cost, and service life of the range of treatment alternatives from which the selection can be made.

The procedures in the handbook are devised on the basis of the concepts developed in Part I of this document. The results of SHRP research by Cady and Gannon[3] were used to make a reliable determination of the condition of the concrete. Also, the SHRP research by Weyers et. al.[4] was used to develop concepts for determining concrete service life. Both agency costs and user costs have been taken into consideration in conducting life-cycle analysis.

1.3 Scope

The methodology in its present form only applies when the predominant concrete deterioration is associated with chloride-induced corrosion of the reinforcing steel.

The procedures outlined in the handbook are primarily devised for exposed concretes, but they also apply to covered concretes. Where a procedure does not apply to covered concretes, adjustments have been made for covered concretes and explained.

The procedures in the handbook determine the life-cycle cost when the concrete is treated at the present or in the future. Those procedures, however, can be employed to determine the life-cycle cost if the concrete was treated in the past. Of course, the latter life-cycle cost information cannot be used for planning a treatment. However, it could be used to compare strategies.

The methodology is designed to be flexible and can be tailored to suit the needs of the individual highway agencies. The user has the option of deleting those aspects of the methodology that are irrelevant to a specific case.

2. Overview of the Handbook

This chapter provides the user with an overview of the handbook and prepares the user for the details of the methodology that follow in the next 11 chapters. Those 11 chapters (i.e., Chapters 3 through 13 of the handbook) provide a step-by-step procedure to lead the user to the appropriate treatment of a specific concrete component: that is, what type of treatment to apply, and when to apply it for maximum cost-effectiveness. The answer is obtained by conducting the life-cycle cost analyses found in Chapter 13. Chapters 3 through 12 are background chapters and provide the necessary information on service lives and costs that are input into Chapter 13 to conduct life-cycle cost analyses. Chapter 14 includes an example with calculations and illustrates how the methodology is applied to a realistic bridge component.

2.1 How to Use the Handbook

To use this handbook, the user should first become familiar with the methodology by reviewing Chapters 3 through 13. Chapter 13 can then be used for any specific case to determine the most cost-effective strategy. In Chapter 13, references are systematically made to Chapter 3 through 12 to gather the input information required. The next several pages outline and briefly discuss Chapters 3 through 13.

2.2 Chapter 3: Service Life Limitation due to Functional Features

This chapter addresses functional features of the bridge, so that if the remaining service life of the whole structure is unusually short because of functional features, that will be taken into account later, when making a decision on the component treatment. This is important, since the methodology employs life-cycle cost analysis to determine the most cost-effective treatment strategy.

2.2 Chapter 4: Testing Concrete

This chapter provides the user with a guide for obtaining site-specific test data that are essential to the methodology. The following tests are needed:

- Visual survey and detection of spalls.
- Delamination detection.
- Bar cover depth measurement.
- Chloride content measurement.

The following tests are only needed when the concrete presents certain conditions:

- Half cell potentials survey.
- Rate of corrosion measurement.
- Permeability/resistivity measurement.

2.3 Chapter 5: Condition Determination

Chapter 5 deals with determining the condition of concrete. The chapter presents a systematic procedure to employ the test data obtained in Chapter 4 to quantify the condition in terms of an index (condition index of 100 or lower). The test data employed relate to spalling, delamination, and chloride contamination of the concrete.

As a concrete bridge component ages, its condition gradually changes and its condition index increases to a point where some type of treatment must be done. The condition index corresponding to the "must" condition will be selected by the user on the basis of structural considerations and/or the ride quality of the deck. The chapter recommends a default value for the maximum tolerable condition index.

2.4 Chapter 6: Prediction of Performance

In this chapter a systematic procedure is presented for predicting the condition index of concrete at any given time in the future. This is done through a performance equation that relates the condition index to the age of concrete. There are two parameters in the equation which are systematically determined from the site-specific data. Nomograms have been prepared as an alternative to hand calculations to determine the two parameters of the performance equation.

2.5 Chapter 7: Evaluation of Performance

Chapter 6 established a performance equation which relates the concrete condition to the age of concrete. Chapter 7 will assist the user to understand the rate of deterioration of the concrete by illustrating the equation graphically. On the basis of two parameters of the performance equation obtained in Chapter 6, the user will select the performance curve from a family of curves.

From the performance curve, the user will define the period of time between present time and time corresponding to the maximum tolerable condition index (determined

from Chapter 5). This is the "treatment consideration period." The rest of the handbook is used to determine the timing of the treatment within the "treatment consideration period," as well as the type of the treatment, for maximum cost-effectiveness.

2.6 Chapter 8: Compatible Treatment Alternatives

This chapter will provide a range of treatment alternatives from which the selection can be made. Prior to selecting all of the treatment alternatives in this chapter, the user will consult the tables provided, screening out those alternatives which are not compatible with the concrete because of their technical disadvantages.

2.7 Chapter 9: Cost Items Associated with Treatment (Agency Costs)

Costs associated with various treatments should be known so that life-cycle cost analysis can be conducted. Cost can vary significantly from one area to another depending on many factors. The user generally has most reliable information regarding cost of a certain treatment in a given jurisdiction. However, before the user arrives at any cost for a treatment, the standard cost items associated with that treatment must be identified.

Chapter 9 will provide standard highway agency cost items associated with each treatment covered in the handbook.

2.8 Chapter 10: Cost Items Associated with Treatment (User Costs)

Two types of user costs are considered in this chapter: (1) prior-to-treatment costs (decks only), and (2) during-treatment costs. Costs in the period prior to the treatment are a function of the condition of the bridge deck and its effect on traffic flow. A badly spalled deck would impede traffic flow, causing speed reduction, and congestion and resulting in increased travel time and cost. Costs during the treatment are related to increases in travel time caused by traffic congestion on the bridge or by detours around the bridge during bridge closure. Nomograms are provided for determining the user costs, as an alternative to the equations.

2.9 Chapter 11: Decomposing Concrete Condition Index

In order to estimate agency costs and user costs associated with a treatment (Chapters 9 and 10), the amount of concrete repair (removal and replacement of deteriorated and possibly contaminated concrete) needs to be predicted at the time of treatment. The amount of deterioration and contamination in the future can be predicted by decomposing the future concrete condition index into its component parts (i.e., chloride

contamination, delamination, and spalling). This chapter will provide a systematic procedure for decomposing the condition index.

2.10 Chapter 12: Prediction of Performance after Treatment

The methodology employs life-cycle cost analysis to determine cost-effectiveness. Therefore, the service life of the concrete after the treatment, also, needs to be predicted. Generally, two factors affect the performance of the concrete after the treatment. Those are (1) the inherent corrosion mechanism active at the time of treatment, and (2) the treatment's effect on the future corrosion process.

Chapter 12 uses the concept of "trend in the rate of corrosion after treatment" to determine the effective service life of the concrete after the treatment. Equations and nomograms, as alternatives to the equations, are presented for this purpose. The procedure does not depend on the actual rate of corrosion, unless concrete presents certain conditions.

2.11 Chapter 13: Optimum Treatment and Time of Treatment

Having determined: (1) the concrete performance, (2) the "treatment consideration period," (3) compatible treatment alternatives, (4) how to determine costs associated with a treatment, and (5) the performance after the treatment, the user must decide what type of treatment to apply and when to apply it within the "treatment consideration period," for maximum cost-effectiveness. Chapter 13 deals with this subject through life-cycle cost analysis.

The user will first determine for each compatible treatment the optimum time of treatment and then will compare the corresponding life-cycle costs in order to prioritize those compatible treatments. This is discussed below.

For simplicity, for each compatible treatment, the user will consider treating the concrete component at three points during the treatment consideration period: (1) the present time, (2) the time corresponding to the maximum tolerable condition index, and (3) some time between those two.

The economic analysis of the three possible strategies described will be done within a set time frame called the "planning horizon." The planning horizon begins with the present time and extends for 20 years. However, if the service life of the component is limited because of the bridge's functional features, the planning horizon will be the remaining service life of the structure, as discussed in Chapter 3.

All costs associated with each strategy, including the cost of repeated cycles of treatment within the planning horizon are then discounted and totaled for comparison with the other strategies. At the end of this economic analysis, the user will be able to determine

the optimum strategy (time of the treatment) for a compatible treatment. Also, the user will be able to prioritize the various compatible treatments based on their life-cycle costs. A worksheet has been prepared to facilitate life-cycle cost analysis.

3. Service Life Limitation Due to Functional Features

If, when the current criteria for serviceability are applied, the bridge will be functionally obsolete in the near future, then the component treatment must be compatible with the remaining life of the structure as a whole. Life-cycle costs of various strategies can be affected by the remaining service life of the structure, as discussed in Chapter 13.

Bridge functional features that can limit the remaining service of a bridge include

- width,
- clearance,
- alignment, and
- load limits.

The user should estimate the remaining service life of the bridge if the bridge functional features limit the remaining service life to 30 years or less. If the exact remaining service life is not known, one of the ranges shown below may be chosen to the best of the user's knowledge.

- 0 - 5 years
- 5 - 10 years
- 10 - 15 years
- 15 - 20 years
- 20 - 25 years
- 25 - 30 years

If a range is chosen, then the maximum of that range will be used as the remaining service life in Chapter 13.

If the remaining service life is estimated at higher than 30 years, it may be assumed unlimited for the purpose of life-cycle cost analysis in this handbook.

4. Testing Concrete

This chapter guides the user through obtaining site-specific test data that are essential to the methodology. Tests included in this chapter are discussed in detail in SHRP research by Cady and Gannon[3] and other sources cited in this handbook. Those tests investigate concrete element deterioration due to reinforcement corrosion. If non-corrosion deterioration is identified as significant, this handbook may not produce viable results.

4.1 Tests Required

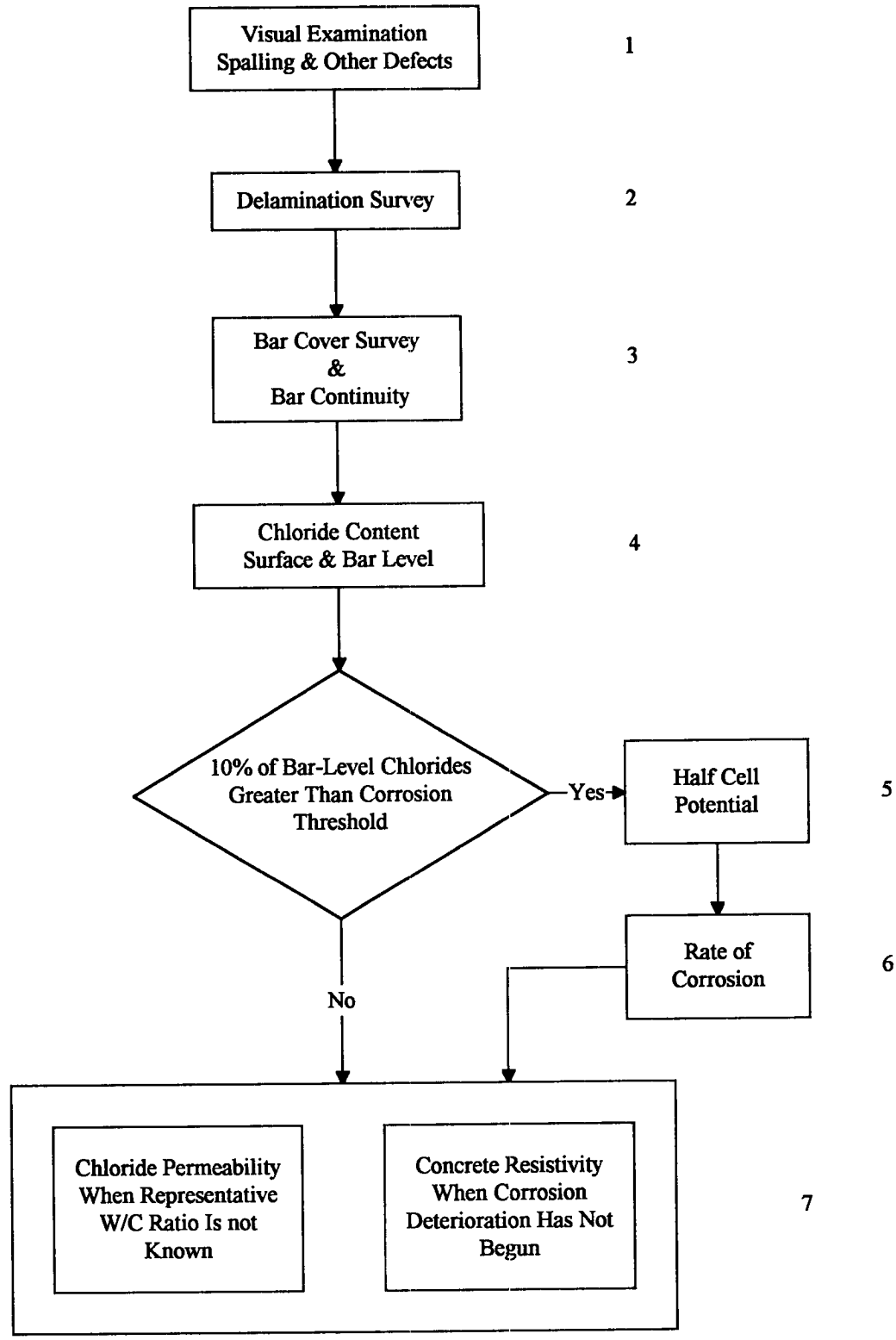
The tests required, and the order in which they are conducted, are given in Figure 4.1. First, a visual examination of the member is conducted to determine the area of concrete spalling and to determine if other non-corrosion related deterioration is present. Next, the amount of concrete delamination (internal concrete cracking caused by bar corrosion) is obtained. This quantity does not include spalls. Third, a bar cover depth survey is conducted, and bar electrical continuity within the element is determined. Fourth, concrete chloride content profiles are obtained. The profiles give chloride content at the surface and at the bar level. Fifth, a half cell corrosion potential survey is conducted to obtain areas of highest potential. Sixth, rate of corrosion is determined in the areas of highest half cell potential. Note that the fifth and sixth activities (i.e., half cell test and rate of corrosion test) are generally not required (except where concrete was repaired/rehabilitated, previously); however, they are performed to support, and modify if necessary, concepts used in the methodology. Also, those two activities need not be considered when less than 10 percent of the bar-level chloride contents are greater than, or equal to, the corrosion threshold chloride content.

Additionally, testing concrete for chloride permeability and/or resistivity may be required when

1. water-cement ratio of the concrete is not known (testing the concrete for permeability),

2. permeability of a special concrete, overlaying the concrete, is questionable (testing the overlay for permeability), and

Figure 4.1. Tests Required



3. the concrete has not yet shown the first sign of corrosion-induced deterioration (testing the concrete for resistivity).

4.2 Number of Tests and Samples

The procedures in Table 4.1 are given with suggestions for the number of tests and samples to obtain from various bridge components.

4.3 Test Descriptions

The following chapters discuss the individual evaluation methods.

Visual Examination

A visual examination of the concrete surface is used to determine the extent of deterioration and forms the basis for the subsequent concrete condition surveys. The visual examination described here is not related to the bridge survey system adopted by Federal Highway Administration[8]. The visual examination notes both corrosion and non-corrosion related deterioration. It should note size, location, and orientation of

1. spalls,
2. patches (temporary and permanent),
3. scaling,
4. pop-outs,
5. cracks, and
6. wheeltrack wear (only bridge decks).

These items should be shown on a sketch. A grid layout is established on the concrete surface to map concrete deficiencies and to determine their ***magnitude*** based on a percent of surface area. The ***severity*** of the deterioration should be determined quantitatively during a visual examination by simply measuring the depth of spalls, scaling, and wheeltrack wear. Exposed and corroding reinforcing steel should also be noted.

The visual examination generates a comprehensive condition survey of the concrete surface. It determines the extent of corrosion-induced spalling, as well as the significance of deterioration caused by reasons other than corrosion of the reinforcing steel. The output of this procedure for use in the calculations is the percent of the area which has spalls, temporary patches covering spalls (e.g., asphalt patches), and permanent patches (e.g., concrete patches).

This methodology cannot be used to determine remedial actions for non-corrosion-related deterioration (e.g., scaling, pop-outs, surface cracking, and wheeltrack wear). If

Table 4.1. Number of Tests and Samples

Procedure	Methodology
Visual Examination	Use 5-foot grid on deck (2.5-foot grid on sub- and superstructure) to locate defects.
Delamination Survey	Use 5-foot grid on deck (2.5-foot grid on sub- and superstructure) to locate all areas of delamination. Distinguish between delaminations and spalls.
Cover Depth	The greater of (1) 40 locations per member or (2) N=40(A/5000) locations per member, where A= area in square feet of member.
Chloride Profiles	The greater of (1) 10 locations per member or (2) N=10 (A/5000) locations per member, where A= area in square feet of member.
Corrosion Potential	Use 5-foot grid on deck (2.5-foot grid on sub- and superstructure). Additional measurements required to locate sites of anodic (highest) potential.
Corrosion Rate	Measurements at sites of anodic corrosion potentials; limited to the greater of (1) 10 locations per member or (2) N=10(A/5000) locations per member, where A = area in square feet of member.
Concrete Permeability/Resistivity	The greater of (1) 2 locations per member or (2) N=2(A/5000) locations per member, where A= area in square feet of member.

- One foot is 0.305 meter
- One square foot is 0.093 square meter

non-corrosion-related deterioration is significant, the most cost-effective treatment may be obtained by considering factors which are not covered in this methodology.

Delamination Survey (ASTM D4580)

This test (ASTM D4580) is used to survey concrete by sounding the surface to determine the presence of delaminations (corrosion-induced internal cracks). To conduct this test, first a grid layout is established on the concrete surface. Second, the surface is sounded and delaminations noted. Third, the areas of delamination are marked and mapped for the report. Fourth, the amount of delamination is computed as a percentage of the surface area. Spalls **are not** included.

Where rigid overlays are applied, the test (ASTM D4580) shall distinguish delaminations from debonding of the overlay. Where asphalt concrete overlays are applied, delaminations and/or debonding should be detected using the procedure recommended by SHRP's test method, "Standard Test Method for Assessing the Condition of Asphalt-Covered Bridge Decks Using Pulsed Radar." The SHRP test method is documented in Appendix B of Cady and Gannon.[3]

If overlay debonding is significant, the most cost effective treatment may be obtained considering factors which are not covered in this methodology.

Cover Depth over Reinforcement Using a Cover Meter (Magnetic Flux Device)

This device uses a magnetic field to detect reinforcing steel within hardened concrete. It can determine the location, orientation, size, and depth of the bar. The accuracy of the device in measuring the depth of cover decreases as the depth of cover increases. Magnetic particles in the concrete can influence the measurements. Thus, a correction factor should be obtained by exposing the bar at one location and measuring the actual depth. Usually, the correction factor is obtained at a location which can later serve as the half cell test bar ground connection.

If the bar size is not known, the depth cannot be read directly from the scale; therefore, the following technique is suggested.

1. Locate the bar in the test area.

2. Place a two-by-four or other non-metallic spacer, between the probe and the concrete surface.

3. Record possible bar size and depth combinations.

4. Correct readings for the thickness of the spacer by subtracting its thickness.

5. Place the probe directly on the concrete surface and record possible reading.

The bar size for which the same cover depth is obtained in Steps 4 and 5 is the correct result.

Reinforcing Steel Electrical Continuity

Electrical continuity of the reinforcing steel should be known prior to conducting certain tests or applying certain treatments. Electrical continuity can be determined by measuring the resistance between widely separated steel components. Low resistivities indicates continuity.

Chloride Profiles (AASHTO T260-84, or SHRP Modified Test Method)

This test determines the chloride content of concrete. Concrete powdered samples are collected with a vacuum bit near the concrete surface (0.25 inch to 0.75 inch (0.6 centimeters to 1.9 centimeters) depth) and at the level of the reinforcing steel (the bottom 0.25 inch (0.6 centimeters) of concrete cover). Where a concrete overlay is applied, "concrete surface" is the surface of the overlay.

The SHRP "Standard Test Method for Chloride Content in Concrete Using the Specific Ion Probe" is documented in Appendix F of Cady and Gannon.[3] In the SHRP test method, which is a field method, the powdered samples are dissolved in, and stabilized by, two solutions. A probe is then inserted into the mixture and the readings are recorded in the field. Calculations convert readings into chloride content expressed as a percentage of concrete weight.

AASHTO T260-84 test method may be used for chloride content determination.

Corrosion Potential Survey (ASTM C876)

This procedure (ASTM C876) determines the potential for the existence of reinforcing steel corrosion through measuring the electrical potential of the reinforcing steel. It may be performed if 10 percent of the chloride samples at the depth of the steel are greater than the corrosion threshold chloride content.

The procedure for administering this test follows:

1. Establish a grid on the concrete surface.

2. Provide an electrical connection to the steel (ground).

3. Place a half cell corrosion detection device on the concrete surface at the grid points.

4. Record the electrical potential readings.

Note that the test cannot be conducted in the absence of the electrical continuity of the reinforcing steel.

This procedure obtains the location of highest half cell potentials (peak negative potentials) for the subsequent rate of corrosion testing. The location of highest potentials can be obtained in the field by scanning the concrete surface around the anodic areas with a half cell device. The locations of anodic areas are obtained by plotting the grid half cell potentials and drawing equipotential contour lines.

The corrosion potential survey is not recommended for epoxy-coated or galvanized reinforcement. This is because epoxy-coated bars are electrically insulated from each other, and readings on galvanized bars indicate the potential of the zinc coating. Also, the test cannot be conducted where concrete is overlaid with a dielectric material, such as a membrane, polymer material, or asphalt, unless the asphalt is saturated.

Rate of Corrosion Measurement

The SHRP "Standard Test Method for Determining Instantaneous Corrosion Rate of Uncoated Steel In Reinforced Concrete" is documented in Appendix A of Cady and Gannon.[3]

The test should be conducted at locations of highest corrosion potentials (peak negative values) subsequent to the half cell test. Corrosion rate tests should not be carried out where epoxy-coated or galvanized reinforcement is used.

To conduct this test, first mark the bar location and record the bar size and depth. The presence of any lap splices should be noted at the test site. Second, establish an electrical connection to the reinforcement and determine the corrosion potential directly over the bar of interest. Note that the electrical connection provided for the corrosion potential survey can be used for this purpose. Third, use one of the three devices listed below to take readings:

1. The 3LP device by KCC, Inc., USA.

2. NSC device by Nippon Steel Corporation, Japan.

3. Gecor Device by GEOCISA, Spain.

Each device determines the polarization potential of the reinforcing steel. Corrosion current is calculated from a simple equation and expressed in terms of milli-amperes per square foot of reinforcing steel area (mA per sq ft). Note that the three devices listed yield different, but related results. Values obtained by any of the devices may be recalculated into values of another device by using the empirical formulas presented below.[3]

$$\log I_c \text{ (3LP)} = 0.47 + 0.84 \log I_c \text{ (NSC)}$$
$$\log I_c \text{ (GECOR)} = -0.47 + 0.77 \log I_c \text{ (NSC)}$$
$$\log I_c \text{ (GECOR)} = -0.90 + 0.92 \log I_c \text{ (3LP)}$$

Permeability of Concrete (AASHTO T277), and Concrete Resistivity

This test (AASHTO T277) determines the relative permeability of the concrete (or concrete overlay). Many highway agencies are currently using AASHTO T277, "Rapid Determination of the Chloride Permeability of Concrete," which requires coring concrete and conducting a laboratory test. The permeability is indicated by the electrical charge passed through the concrete. The electrical charge is expressed in terms of coulombs.

The concrete samples used for AASHTO T277 test may be used to determine the concrete's "wet" resistivity. A suggested procedure for this purpose is described in Appendix E of Part I of this document. The concrete resistivity is expressed in terms of ohm-centimeters.

5. Condition Determination

The measure of concrete condition is systematically quantified in terms of an index. Three factors are used as indicators of deck condition as affected by corrosion. Those are spalling, delamination, and chloride contamination at the bar level. Of these, when considering repair options at a given time, spalling is the most important, delamination is the second in importance, and chloride contamination at the bar level is the third most important. For purposes of this methodology, the relative importance of each of these factors indicating the need for repair is expressed by assigning the following weights.

- Spalling is 3 times more important than delamination.
- Delamination is 2.5 times more important than bar-level chloride contamination.

The condition index is then quantified using Equation 5.1 or Figure 5.1.

$$S = [CL + 2.5(DELAM) + 7.5(SPALL)] / 8.5 \qquad \text{(Equation 5.1)}$$

and $S <= 100$

where

S = concrete condition index at the time of condition survey and on the basis of condition data expressed as a weighted percentage of the concrete area.

CL = percent of concrete samples with bar-level chloride content higher corrosion threshold value.

[In this handbook, the corrosion threshold value for conventional concrete is assumed 0.035 percent of concrete weight (1.4 pounds per cubic yard (0.82 kilograms per cubic meter)). However, if aggregates with chlorides locked in them, which do not contribute to the corrosion process, are used, the threshold is 0.035 percent (1.4 pounds per cubic yard (0.82 kilograms per cubic meter)) plus the amount of "benign" chlorides. Also, when a corrosion inhibitor admixture is used in the concrete, the threshold is 0.035 percent (1.4 pounds per cubic yard (0.82 kilograms per cubic meter)) plus the increased chloride threshold due to the inhibitor.]

DELAM = percent of concrete area (not including spalls) that is delaminated.

SPALL = percent of concrete area that is spalled.

8.5 = a normalizing factor.

The weighting factors and the normalizing factor used in Equation 5.1 should be considered default values. The user may adjust those values if desired.

As a concrete bridge component ages, its condition gradually deteriorates and its condition index increases to a point where some type of treatment must be done. The maximum tolerable condition index, S_m, will be selected by the user based on structural features of the component and/or ride quality of the deck.

This handbook uses a concrete condition index of 35 as the maximum tolerable index for bridge deck treatment when ride quality is the criterion. The index of 35 represents roughly 50 percent concrete deterioration based on Equation 5.1 (see Chapter 11).

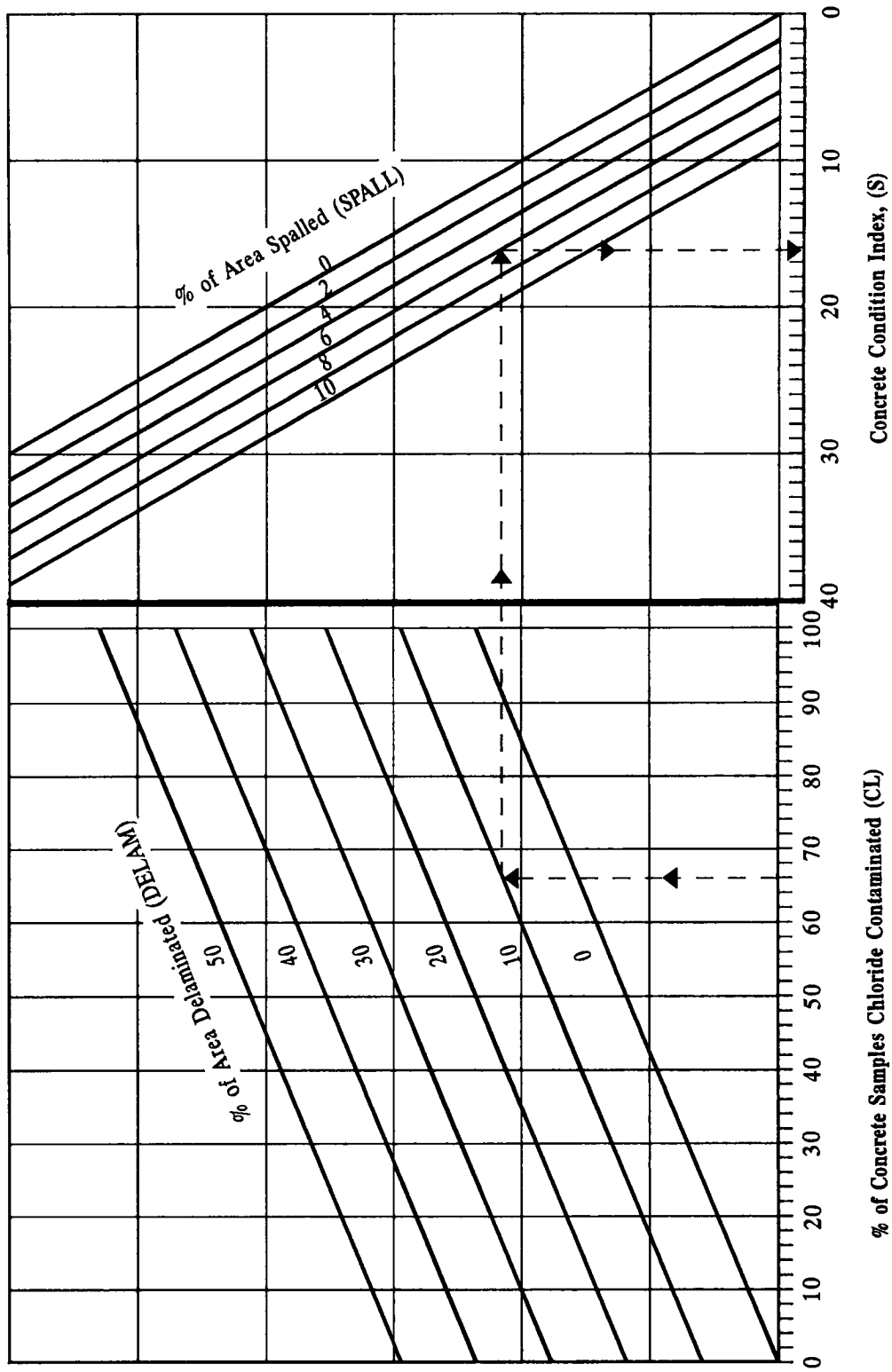


Figure 5.1. Nomogram to Determine Concrete Condition Index, S

6. Prediction of Performance

This chapter presents a systematic procedure for predicting the concrete condition index at any time in the future. Site-specific concrete condition data and concrete engineering properties are used for this purpose.

Three cases are distinguished for the prediction of performance on the basis of construction features, as follows:

1. Concrete repaired, rehabilitated, and/or protected previously.

2. Concrete not repaired, rehabilitated, and/or protected previously, and without a special protection built at the time of initial construction.

3. Concrete not repaired, rehabilitated, and/or protected previously, and with a special protection built at the time of initial construction.

A special protection is a positive protection against corrosion of reinforcing steel, other than quality conventional concrete cover. Typical concrete repair, rehabilitation, and protection systems are presented in Chapter 8.

A predicted concrete condition index is calculated through a performance equation which relates the condition index to the age of concrete. The performance equation used in the methodology, which represents S-shaped curves, is given below.

$$S_t = 100 / [1 + A \exp(-Bt)] \qquad \text{(Equation 6.1)}$$

where

S_t = concrete condition index predicted for concrete age of t

A,B = constants controlling the rate of deterioration and the shape of the curve

t = time since initial construction (age of concrete)

Parameters A and B are determined from site-specific data. One set of data (i.e., condition index and corresponding age) relates to the present (or time of condition

survey, if different). The other set of data relates to the time of first sign of deterioration, unless the concrete was repaired, rehabilitated, and/or protected in the past (See Section 6.1). In that case, the second set of data relates to the time of repair, rehabilitation, and/or protection.

By convention, the concrete condition index at the time of first signs of deterioration, S_d, corresponds to 15 percent chloride contamination at bar level and 0.5 percent delamination. Thus, S_d is equal to 1.9, based on the weighting factors used in Equation 5.1. The concrete age at that time, t_d, is estimated from Equation 6.2, unless stated differently in the handbook. As an alternative to Equation 6.2, Figure 6.1 may be used to determine t_d. [Note that t_d need not be estimated as discussed, if it can be determined from the concrete inspection records.]

$$t_d = [(2.695\ d^{1.22}\ t^{0.21}) / (Z_t^{0.42}\ P)]^{0.8265} \qquad \text{(Equation 6.2)}$$

where

t_d = age of the concrete at time to first signs of corrosion-induced deterioration, years

d = depth of bar cover corresponding to 10th percentile value (average depth - 1.282 standard deviation), inches.

Z_t = surface chloride concentration (from 0.25 to 0.75 inches (0.6 to 1.9 centimeters)) corresponding to 90th percentile value (average + 1.282 standard deviation), percent of concrete weight

t = age of the concrete when Z_t is measured, years

P = concrete water-cement ratio

Figure 6.2 presents the conceptual flowchart of the overall systematic procedure to determine parameters A and B. The following sections detail the procedure in Figure 6.2 and show how to determine the parameters A and B for the three possible cases expected in the field.

Figure 6.1. Nomogram to Determine Age of Concrete at Time to First Sign of Deterioration

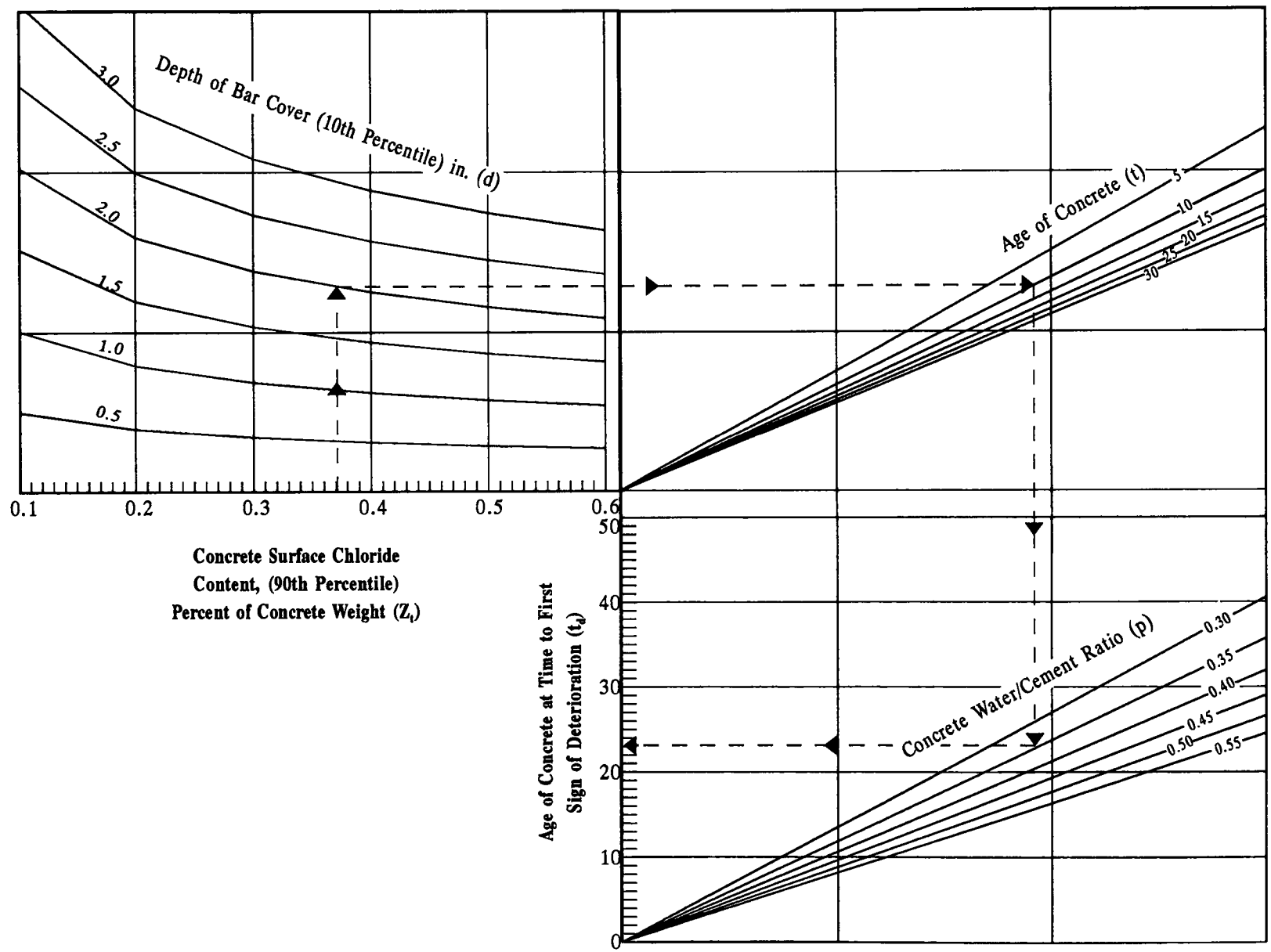
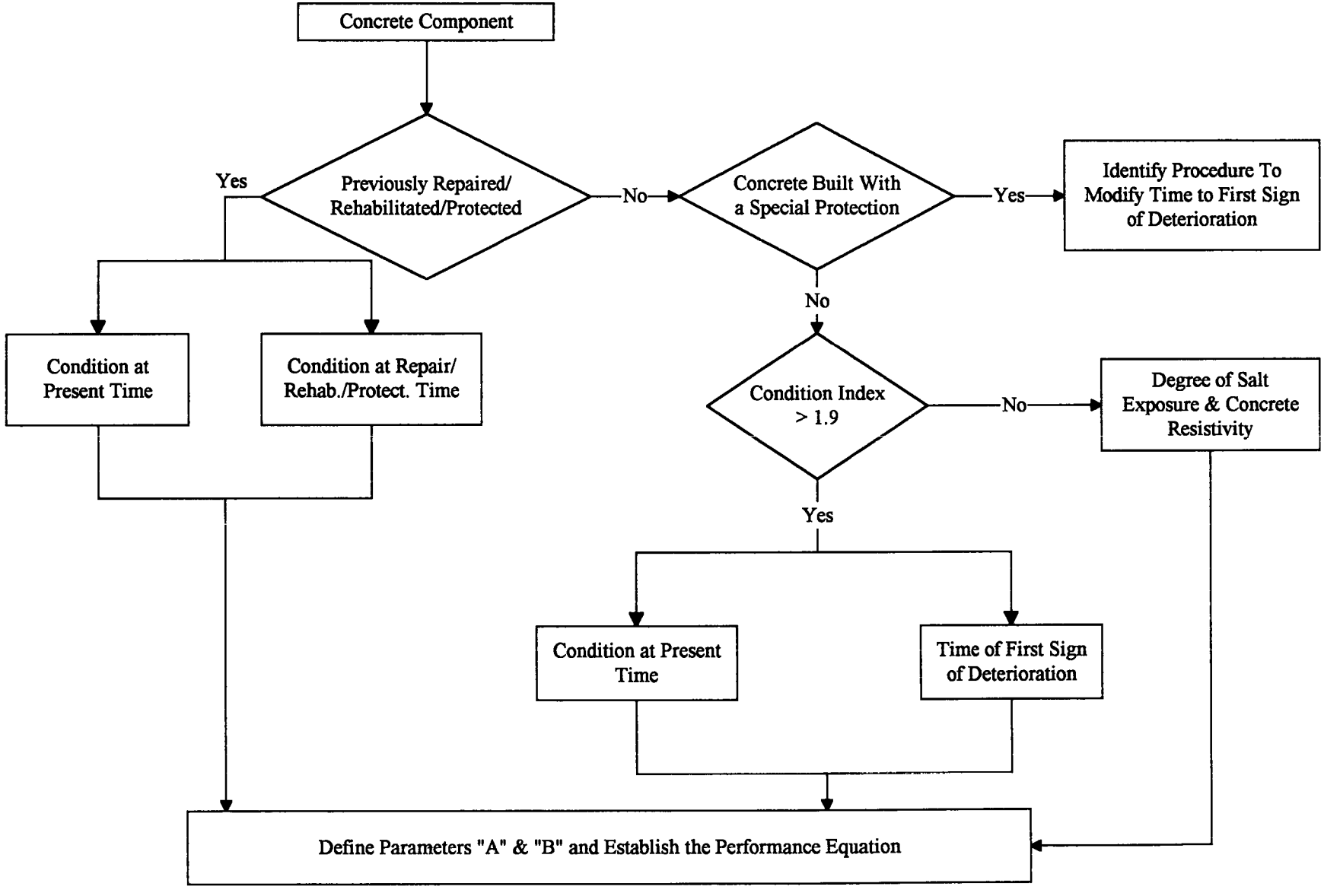


Figure 6.2. Conceptual Flowchart to Determine Concrete Performance Equation



6.1 Case 1: Concrete Repaired, Rehabilitated and/or Protected Previously

This category applies to all concretes which were repaired, rehabilitated, and/or protected against further corrosion-induced deterioration during their service period.

Step 1

Determine the set of data corresponding to present, as shown below.

t_p = age of the concrete at present (or at time of survey, if different), years

S_p = condition index at present (or at time of survey, if different) (Equation 5.1)

Step 2

Determine the set of data corresponding to the treatment, as shown below.

t_r = age of the concrete at repair, rehabilitation and/or protection, years

S_r = condition index at repair, rehabilitation and/or protection (Equation 5.1)

Note that the condition index at repair, rehabilitation and/or protection, S_r, relates to the condition just after the treatment. Usually, at this stage all the deteriorated concrete has been removed and replaced (if any), and the only parameter affecting the condition index is the level of chloride contamination.

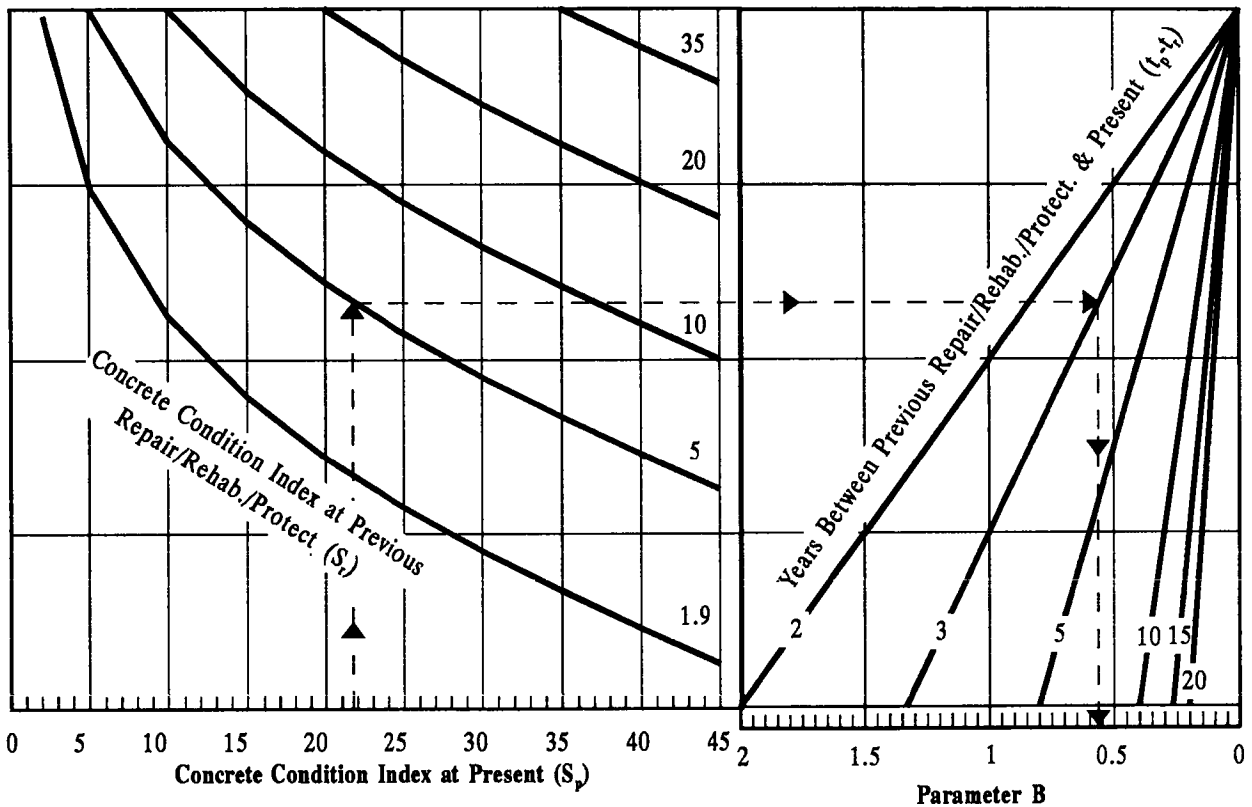
Step 3

Use the following equations to calculate Parameters A and B.
Alternatively, use Figures 6.3 and 6.4 to find B and A, respectively.

$$B = \ln\{[S_r(100 - S_p)] / [S_p(100 - S_r)]\} / (t_r - t_p) \quad \text{(Equation 6.3)}$$

$$A = [(100 - S_p) / S_p] / [\exp(-Bt_p)] \quad \text{(Equation 6.4)}$$

Figure 6.3. Nomogram to Determine Parameter B in Concrete Performance Equation

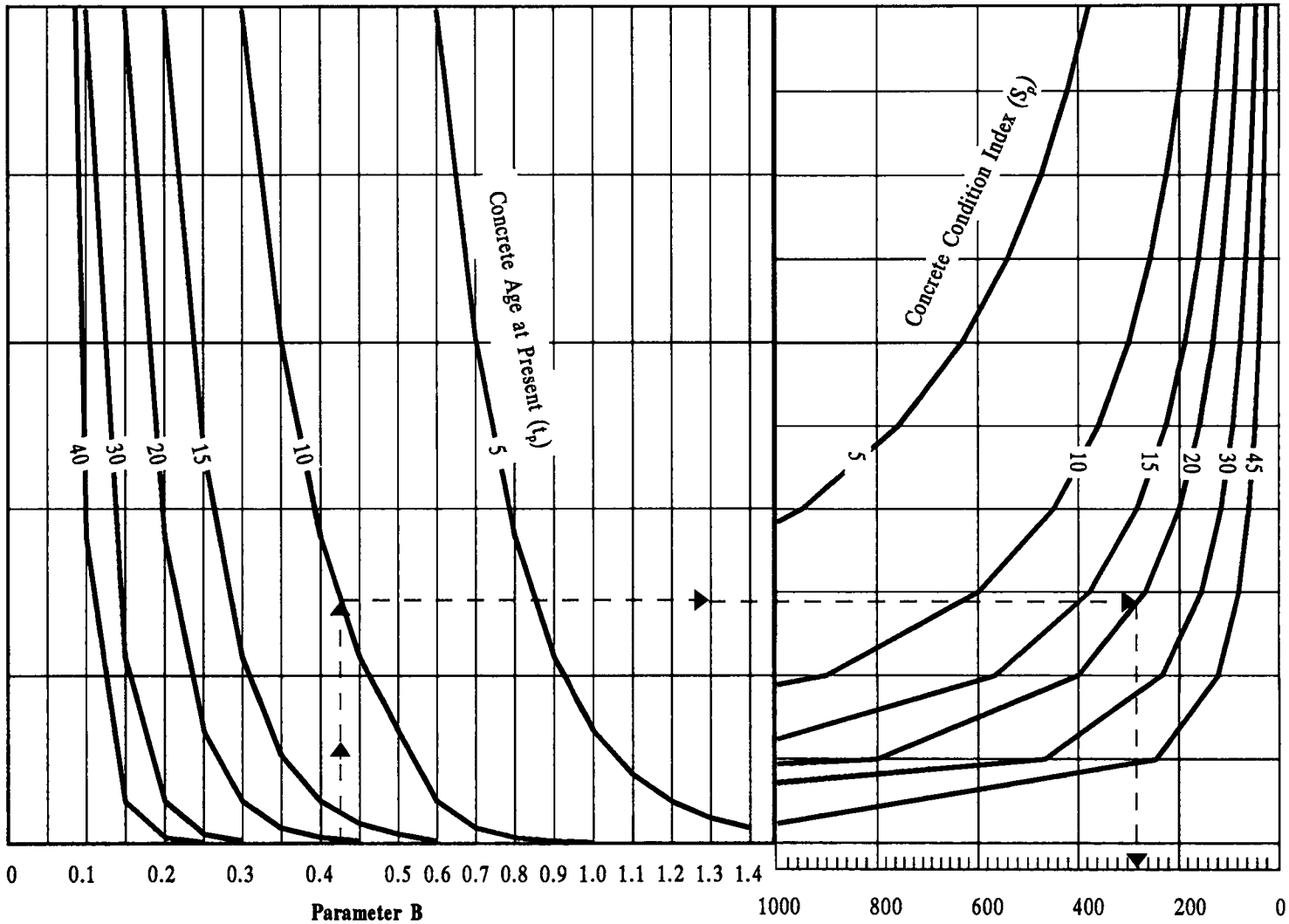


Note:
For Concrete Not Repaired/Rehabilitated/Protected Previously

When $S_p > 1.9$ Use: $S_r = 1.9$, $t_r = t_d$

When $S_p \leq 1.9$ Use: $S_r = 1.9$, $t_r = t_d$ and
$S_p = 45$, $t_p = t_{45}$

Figure 6.4. Nomogram To Determine Parameter A in Concrete Performance Equation



Note:
For Concrete Not Repaired/Rehabilitated/Protected Previously
Use: $S_p=45$, $t_p=t_{45}$ When $S_p \leq 1.9$

6.2 Case 2: Concrete not Repaired, Rehabilitated, and/or Protected Previously and without a Special Protection

This category applies to all concretes which were not repaired, rehabilitated and/or protected against corrosion-induced deterioration during their service period, and were not built with a special corrosion protection system at the time of their initial construction.

Step 1

Determine the set of data corresponding to present, as shown below.

t_p = age of the concrete at present (or at time of survey, if different), years

S_p = condition index at present (or at time of survey, if different) (Equation 5.1)

If condition index S_p is

- greater than 1.9, use Steps 2 and 3;
- less than or equal to 1.9, but greater than 1.2, use Steps 4 through 6; and
- less than or equal to 1.2
  - use Steps 7 through 9, if the surface chloride content (Z_t, Equation 6.2) is > = 0.10 percent of concrete weight (4 pounds per cubic yard (2.4 kilograms per cubic meter)), and
  - use Steps 10 through 13 if the surface chloride content (Z_t, Equation 6.2) is < 0.10 percent of concrete weight (4 pounds per cubic yard (2.4 kilograms per cubic meter)).

Step 2

Determine the set of data corresponding to the first signs of deterioration, as shown below.

t_d = age of the concrete at time to first deterioration, years (Equation 6.2 or Figure 6.1)

S_d = condition index at time to first deterioration, 1.9

Step 3

Use the following equations to calculate Parameters A and B. Alternatively, use Figures 6.3 and 6.4 to find B and A, respectively.

$$B = \ln\{[S_d(100 - S_p)] / [S_p(100 - S_d)]\} / (t_d - t_p) \quad \text{(Equation 6.4)}$$

$$A = [(100 - S_p) / S_p] / [\exp(-Bt_p)] \quad \text{(Equation 6.5)}$$

Step 4

Determine the set of data corresponding to the first signs of deterioration, as shown below.

t_d = same as age of the concrete at present, t_p, years

S_d = condition index at time to first deterioration, 1.9

Step 5

Determine the set of data corresponding to the condition index equal to 45, as shown below.

t_{45} = age of the concrete at condition index of 45, years, as determined from Table 6.1, based on the average wet resistivity of the concrete surrounding the reinforcing steel

S_{45} = condition index of 45

Step 6

Use the following equations to calculate Parameters A and B. Alternatively, use Figures 6.3 and 6.4 to find B and A, respectively.

$$B = \ln\{[S_d(100 - S_{45})] / [S_{45}(100 - S_d)]\} / (t_d - t_{45}) \quad \text{(Equation 6.6)}$$

$$A = [(100 - S_{45}) / S_{45}] / [\exp(-Bt_{45})] \quad \text{(Equation 6.7)}$$

Step 7

Determine the set of data corresponding to the first signs of deterioration, as shown below.

t_d = age of the concrete at time to first deterioration, years (Equation 6.2, or Figure 6.1)

S_d = condition index at time to first deterioration, 1.9

Step 8

Determine the set of data corresponding to the condition index equal to 45, as shown below.

t_{45} = age of the concrete at condition index of 45, years, determined from Table 6.1 based on the average wet resistivity of the concrete surrounding the reinforcing steel

S_{45} = condition index of 45

Step 9

Use Equations 6.6 and 6.7 or Figures 6.3 and 6.4 to find parameters B and A, respectively (see Step 6).

Step 10

Estimate the surface chloride levels in 10 years, based on the level of snowfall and/or exposure to marine environment, as shown in Table 6.2.

Step 11

Determine the set of data corresponding to the first sign of deterioration, using the estimate of surface chloride content in 10 years, as shown below.

t_d = age of the concrete at time to first deterioration, years (Equation 6.2, or Figure 6.1)

S_d = condition index at time to first deterioration, 1.9

Table 6.1. Correlation of Rate of Deterioration and Resistivity

Average Wet Resistivity ohm-cm	Years to Index of 45 (t_{45})
Less than 7,500	t_d + 10
7,500 to 30,000	t_d + 20
Higher than 30,000	t_d + 35

Table 6.2. Estimates of Surface-Level Chloride Content in 10 Years

Snowfall Range, inch[1]	Marine Exposure[1] and Distance from Seawater	Future Surface Chlorides[2] (in 10 years) Whichever is Greater
0 to 3	NO	Z_t (t + 10) / t or 0.04 percent of concrete weight
3 to 12	NO	Z_t (t+10) / t or 0.10 percent of concrete weight
0 to 12	YES > 25 ft	Z_t (t + 10) / t or 0.10 percent of concrete weight
0 to 12	YES < 25 ft	Z_t (t + 10) / t or 0.25 percent of concrete weight
> 12	NO	Z_t (t + 10) / t or 0.25 percent of concrete weight
> 12	YES > 25 ft	Z_t (t + 10) / t or 0.35 percent of concrete weight
> 12	YES < 25 ft	Z_t (t + 10) / t or 0.45 percent of concrete weight

1: One inch is 2.54 centimeters, and one foot is 0.305 meters.

2: "Z_t" is the surface chloride content, percent of concrete weight (divide by 0.025 to convert to pounds per cubic yard, or divide by 0.042 to convert to kilograms per cubic meter), as defined in Equation 6.2. "t" is the duration of exposure when Z_t is measured, years.

Step 12

Determine the set of data corresponding to the condition index equal to 45, as shown below.

t_{45} = age of the concrete at condition index of 45, years, determined from Table 6.1 based on the average wet resistivity of the concrete surrounding the reinforcing steel

S_{45} = condition index of 45

Step 13

Use Equations 6.6 and 6.7, or Figures 6.3 and 6.4, to find parameters B and A, respectively (see Step 6).

6.3 Case 3: Concrete not Repaired, Rehabilitated and/or Protected Previously, and with a Special Protection Built at the Time of Initial Construction

This category applies to all concretes which were not repaired, rehabilitated and/or protected against corrosion-induced deterioration during their service period, and were built with a special corrosion protection system at the time of their initial construction.

Follow all the steps described in **Case 2, Concrete without a Special Protection,** to find the performance equation. However, t_d time to first sign of deterioration, should be modified where Equation 6.2 (or Figure 6.1) is used, based on the type of protective system. The following sections present the types of protective systems and procedures to modify t_d for those systems.

Concrete Overlays:

- Conventional Concrete
- Low-Slump Dense Concrete
- Silica Fume Concrete
- Latex-Modified Concrete

Determine a weighted average water-cement ratio, as shown below, based on the thickness of the overlay and the bar cover depth (excluding the overlay). Input the weighted average water-cement ratio and the total bar cover depth (including the overlay) in Equation 6.2 (or Figure 6.1), and find the modified t_d.

Weighted Average W-C Ratio =

[(Overlay Representative W-C Ratio from Concrete Permeability, AASHTO T277) x (Overlay Thickness) + (Total Cover - Overlay Thickness) x (Base Concrete W-C Ratio)] / [Total Cover] (Equation 6.8)

Membranes, Sealers, Coatings

- Membrane with Asphalt Concrete Overlay
- Penetrating Sealer
- Surface Coating

Determine the number of years the protective system will block the chlorides from penetrating the concrete (effective service life of the protective system), and add it to the number of years found from Equation 6.2 (or Figure 6.1); use the result as the modified t_d.

The effectiveness of membrane and sealer protective system may be checked by test methods described in Cady and Gannon[3].

Concrete Admixtures

- Concrete with Corrosion Inhibitor
- Concrete with Silica Fume

For corrosion inhibitors, determine the number of years the protective system will delay initiation of the corrosion-induced deterioration, based on the amount of inhibitor added to the concrete mix. Add the number of years found to the number of years obtained from Equation 6.2 (or Figure 6.1); use the result as the modified t_d.

For concrete with silica fume admixture, determine a representative water-cement ratio from the concrete permeability value (AASHTO T277) and resistivity value. Input the representative water-cement ratio and the actual bar cover depth in Equation 6.2 (or Figure 6.1), and find the modified t_d.

Coated Reinforcing Steel

- Epoxy-Coated bar
- Galvanized bar

Estimate the number of years to initiation of concrete deterioration with coated bars, and number of years to initiation of concrete deterioration if the bars were not coated. Use the same bar cover depth and water-cement ratio for both cases. Find the difference between the two, and add the difference to the number of years obtained from Equation 6.2 (or Figure 6.1), and use the result as the modified t_d.

7. Evaluation of Performance

Chapter 6 established a performance equation relating the concrete condition to the age of the concrete. This chapter will assist the user understand deterioration of the concrete by illustrating the equation graphically. Use Figure 7.1 to identify the concrete performance curve based on the value of Parameters A and B determined in Chapter 6. For previously repaired, rehabilitated, and/or protected concretes (Case 1, Chapter 6), only consider the portion of the curve beyond the concrete age at repair, rehabilitation, and/or protection, t_r.

As a concrete bridge component ages, its condition gradually deteriorates and its condition index increases to a point that some type of treatment must be done. As discussed in Chapter 5, the user should determine the maximum tolerable condition index, S_m, based on the structural features of the component and/or the ride quality of the deck. The period of time between the present time and time corresponding to S_m is the "treatment consideration period." This is expressed in the following equation.

$$\text{Treatment Consideration Period} = t_m - t_p \qquad \text{(Equation 7.1)}$$

where

t_m = age of concrete when condition index is S_m, determined from the following equation or the performance curve (Figure 7.1), years

$$t_m = -\{\ln[(100 - S_m) / (A \ S_m)]\} / B \qquad \text{(Equation 7.2)}$$

t_p = age of concrete at present, years

The rest of this manual should be used to determine the timing of the treatment within the "treatment consideration period," as well as the type of the treatment, for maximum cost-effectiveness.

Figure 7.1. Concrete Performance Curves, B= 0.10

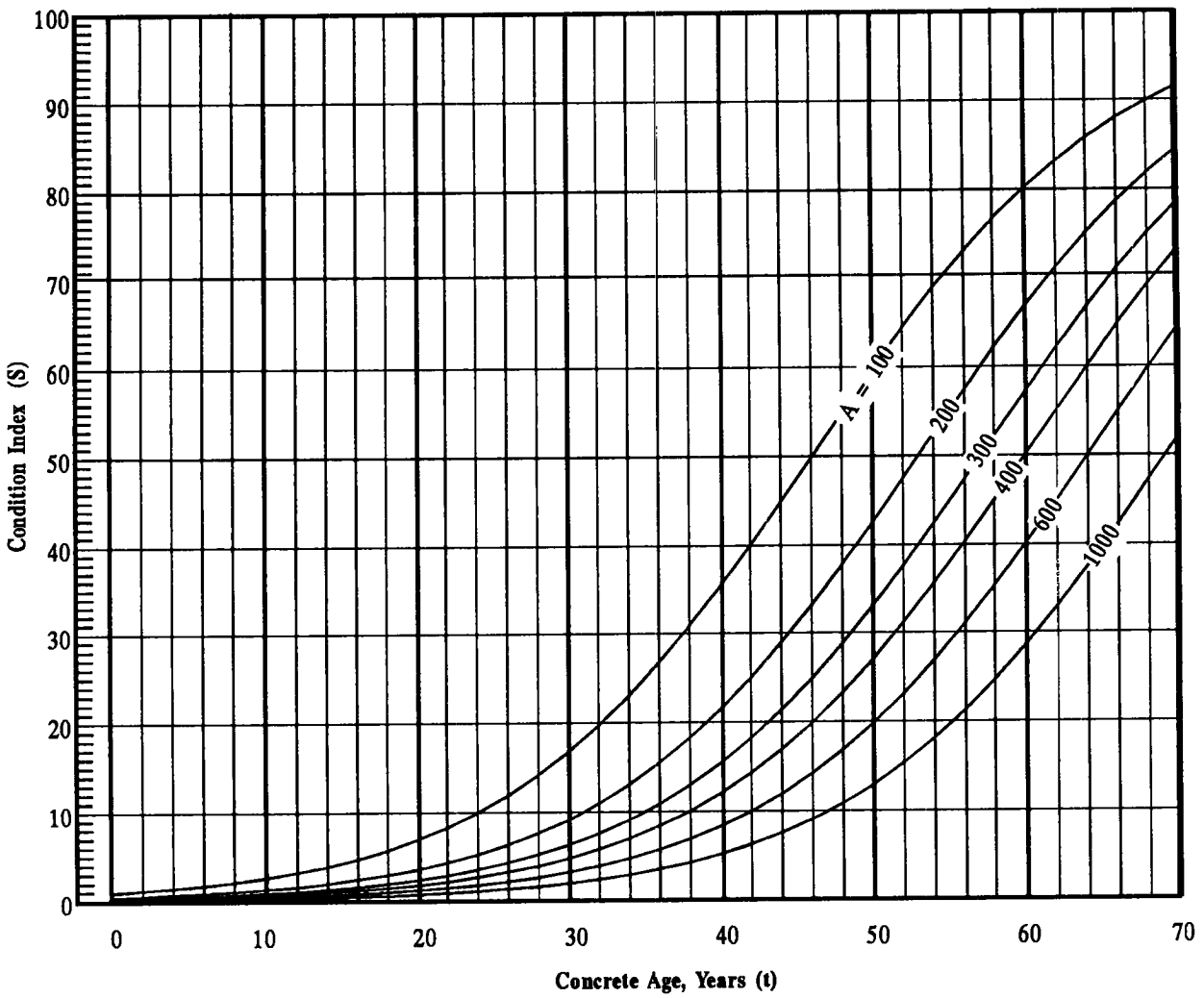


Figure 7.1. (Continued) Concrete Performance Curves, B=.12

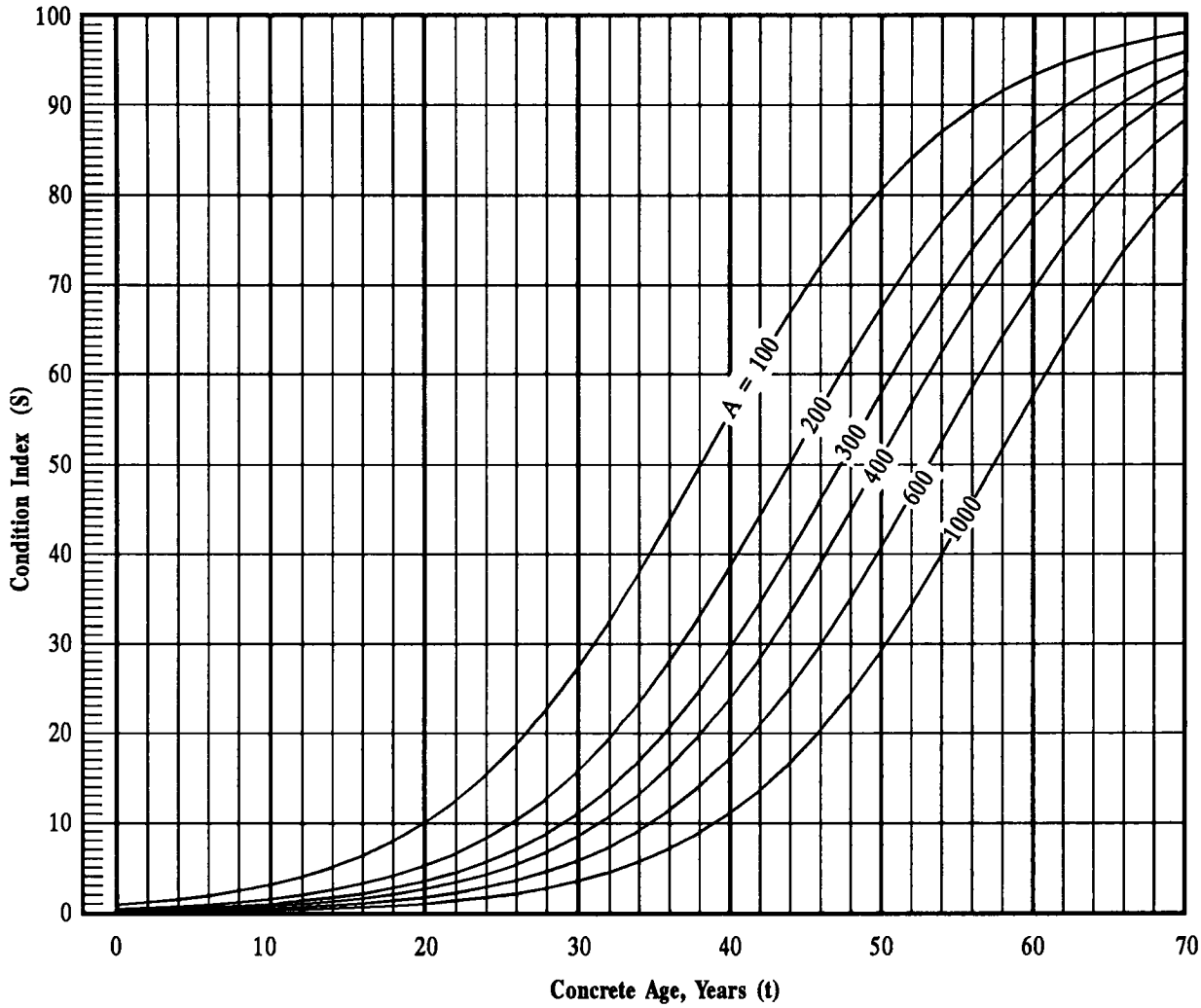


Figure 7.1. (Continued) Concrete Performance Curves, B=.14

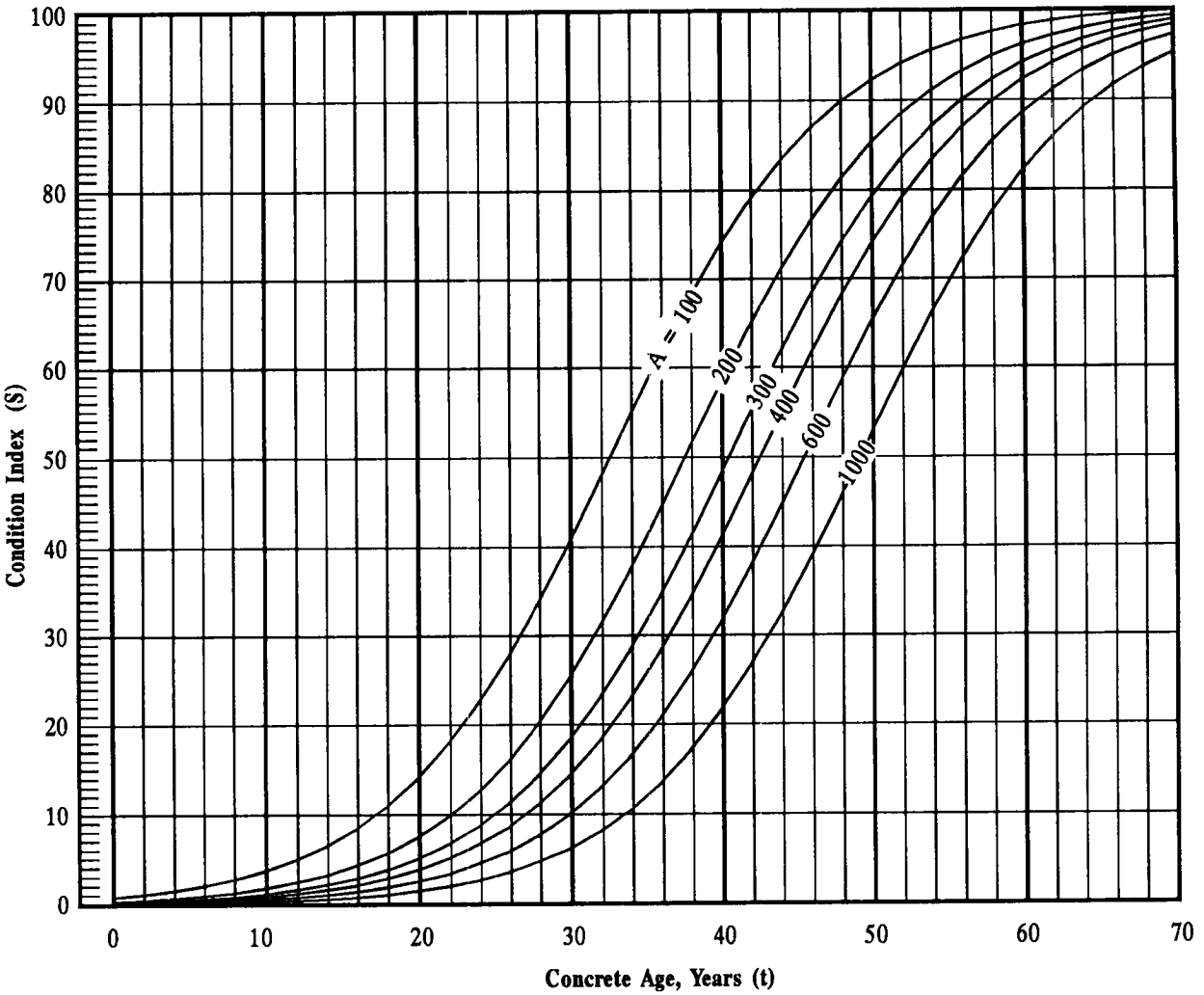


Figure 7.1. (Continued) Concrete Performance Curves, B=.16

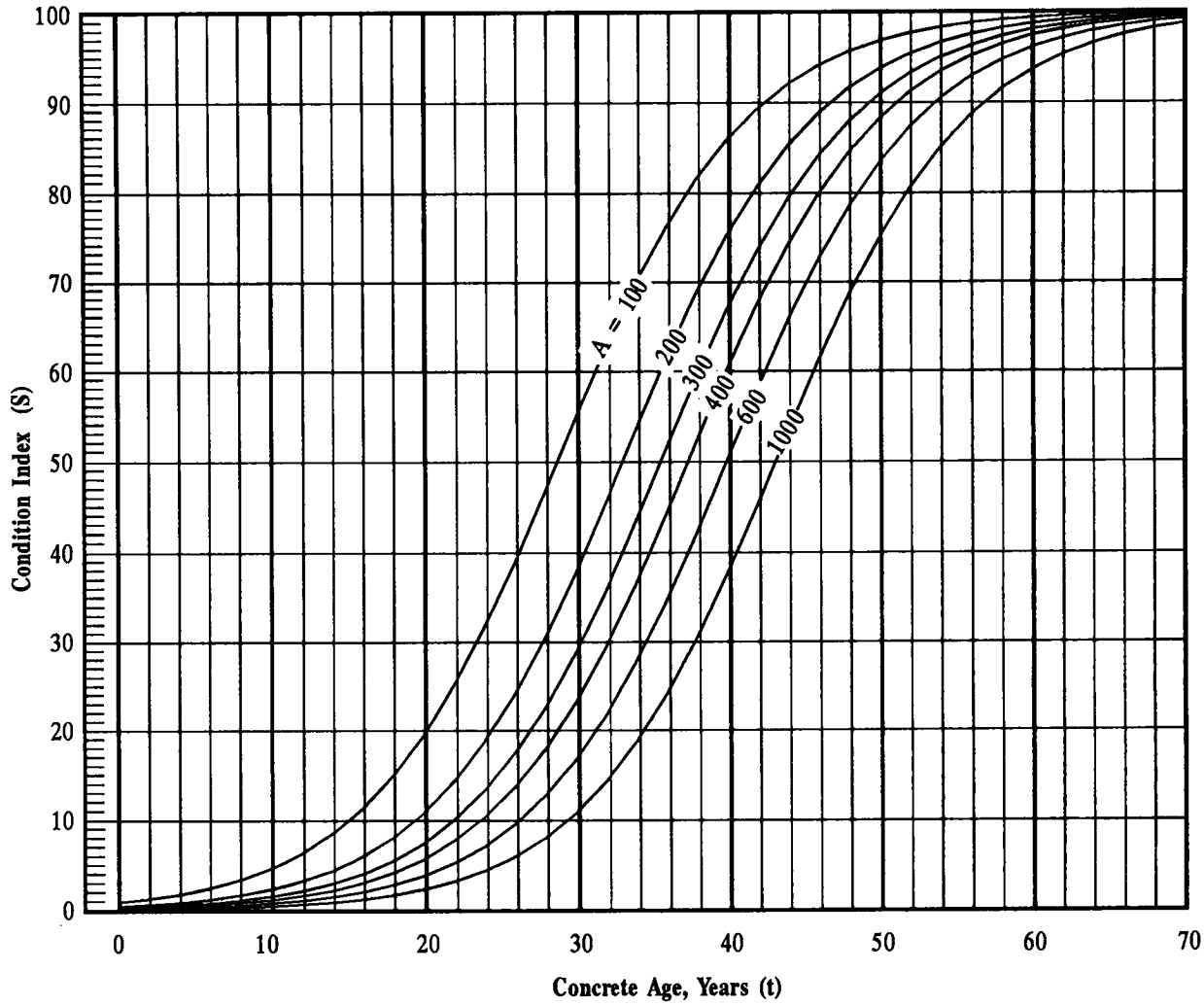


Figure 7.1. (Continued) Concrete Performance Curves, B=.18

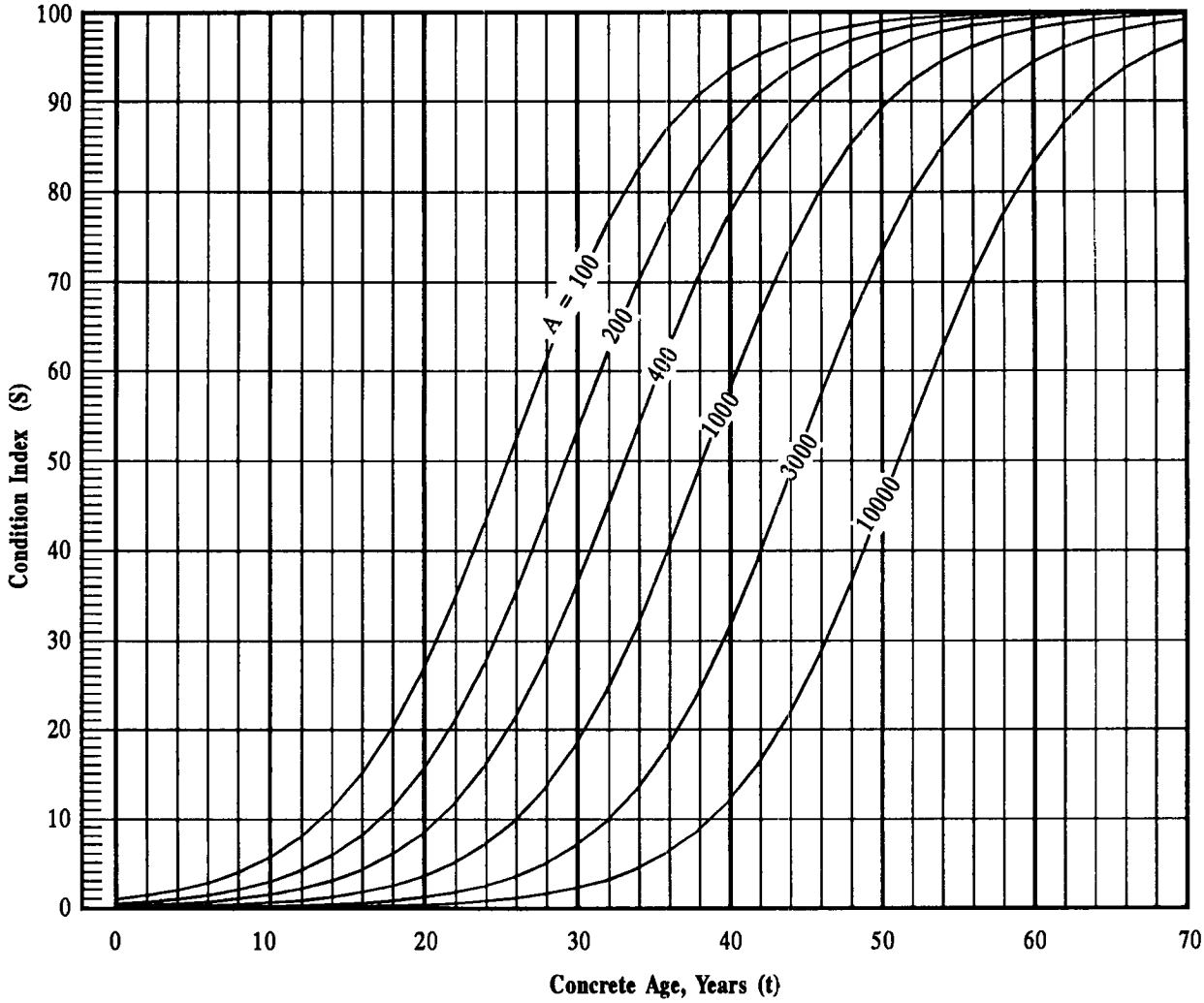


Figure 7.1. (Continued) Concrete Performance Curves, B=.20

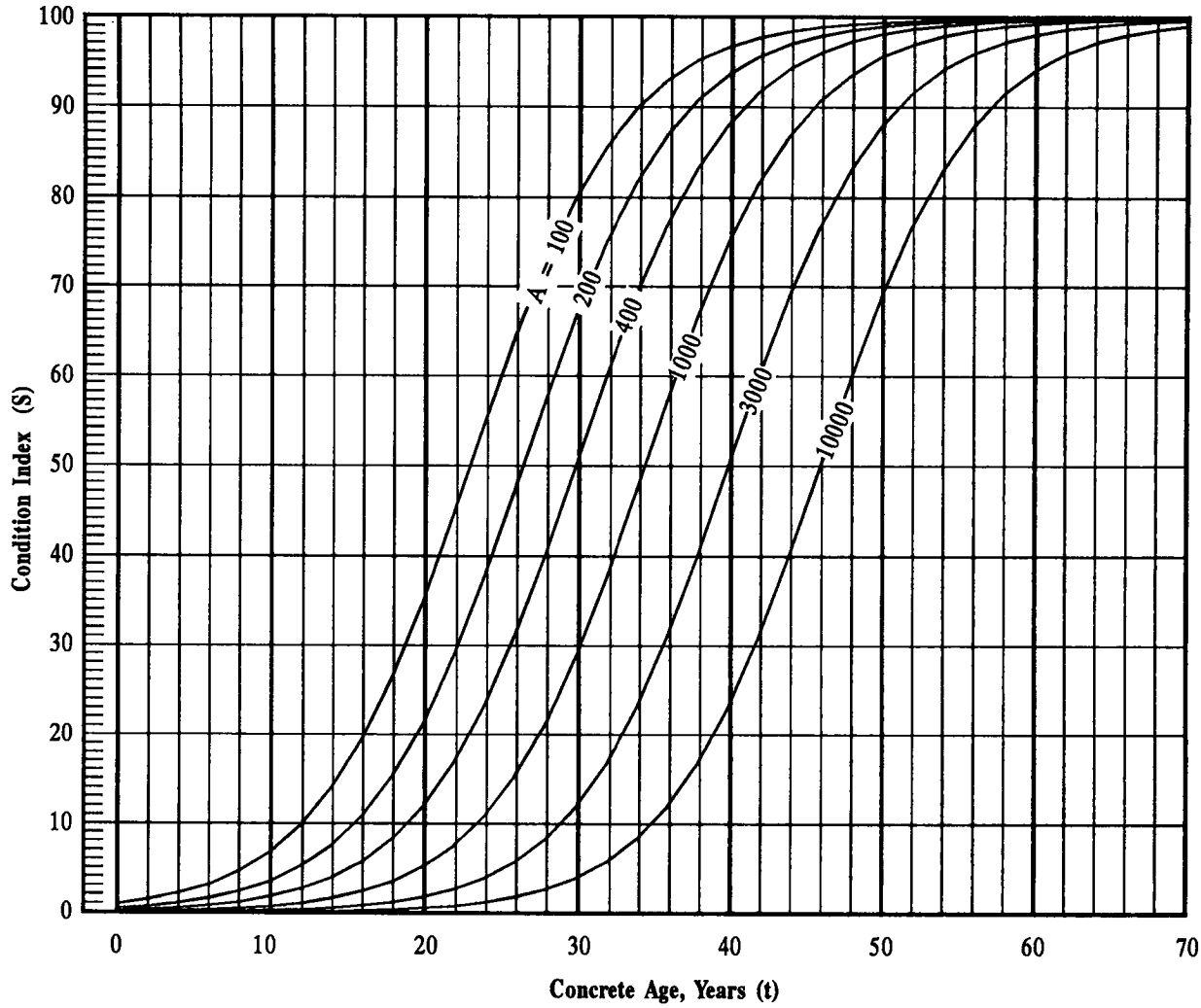


Figure 7.1. (Continued) Concrete Performance Curves, B=.25

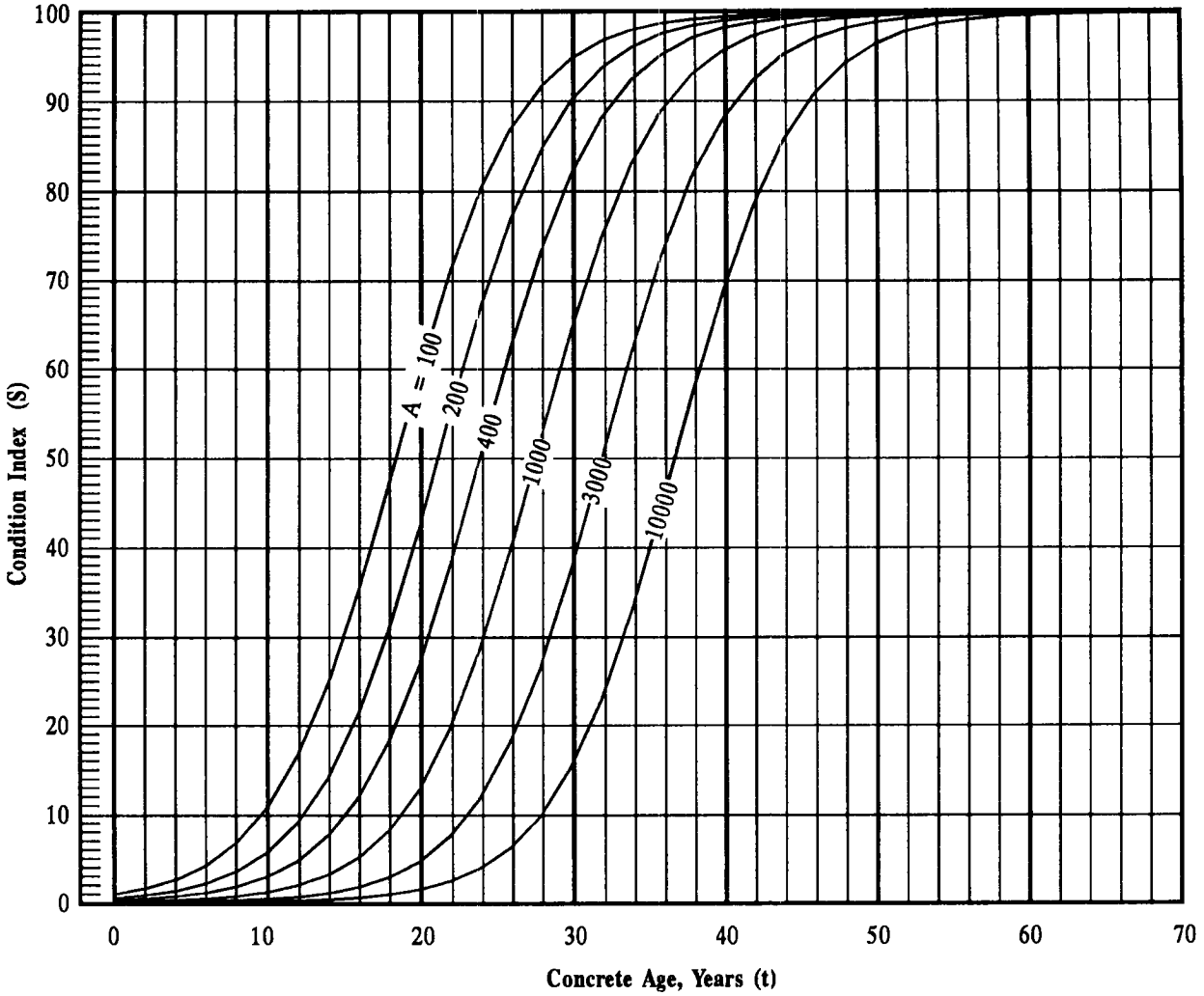


Figure 7.1. (Continued) Concrete Performance Curves, B=.30

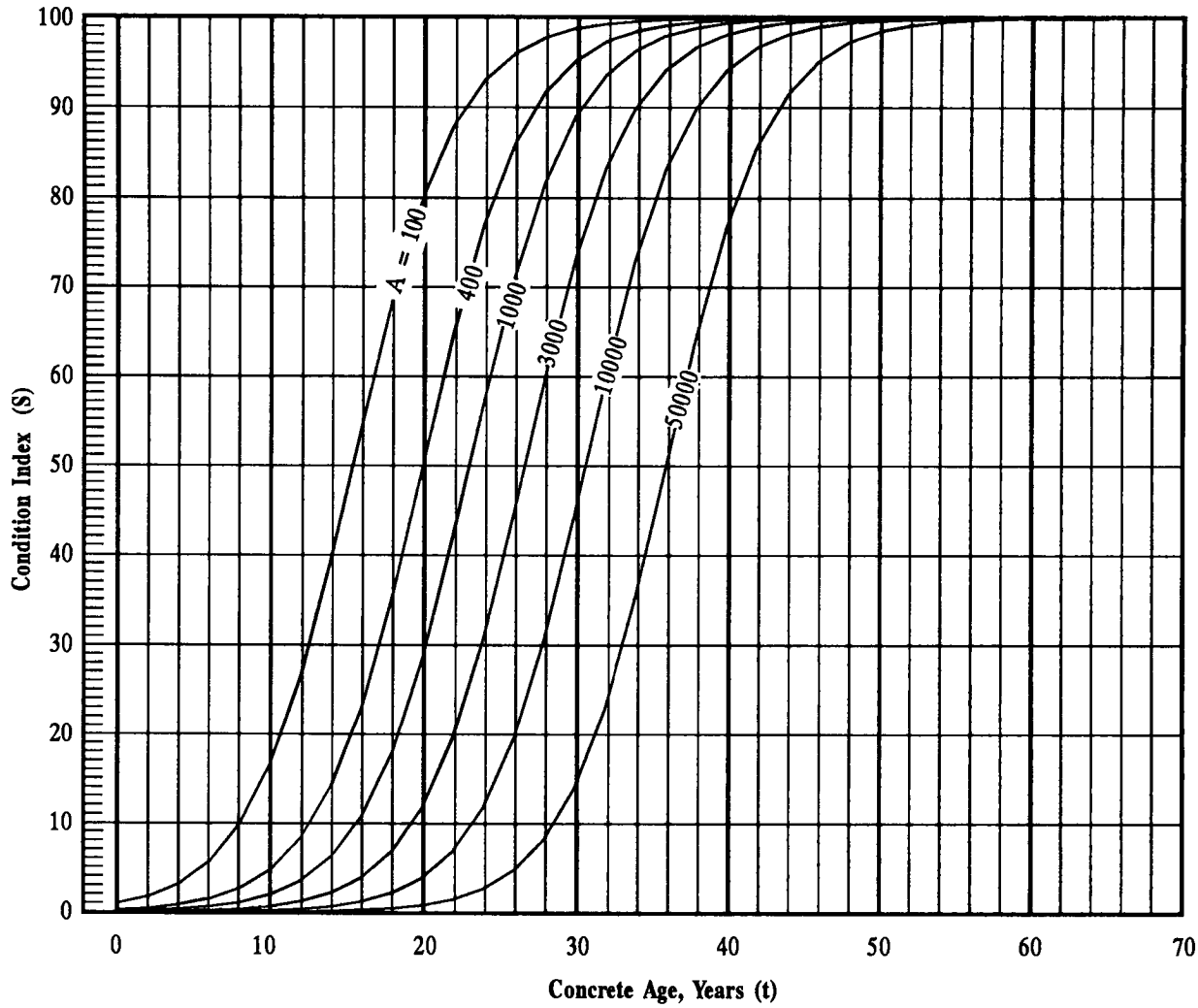


Figure 7.1. (Continued) Concrete Performance Curves, B=.40

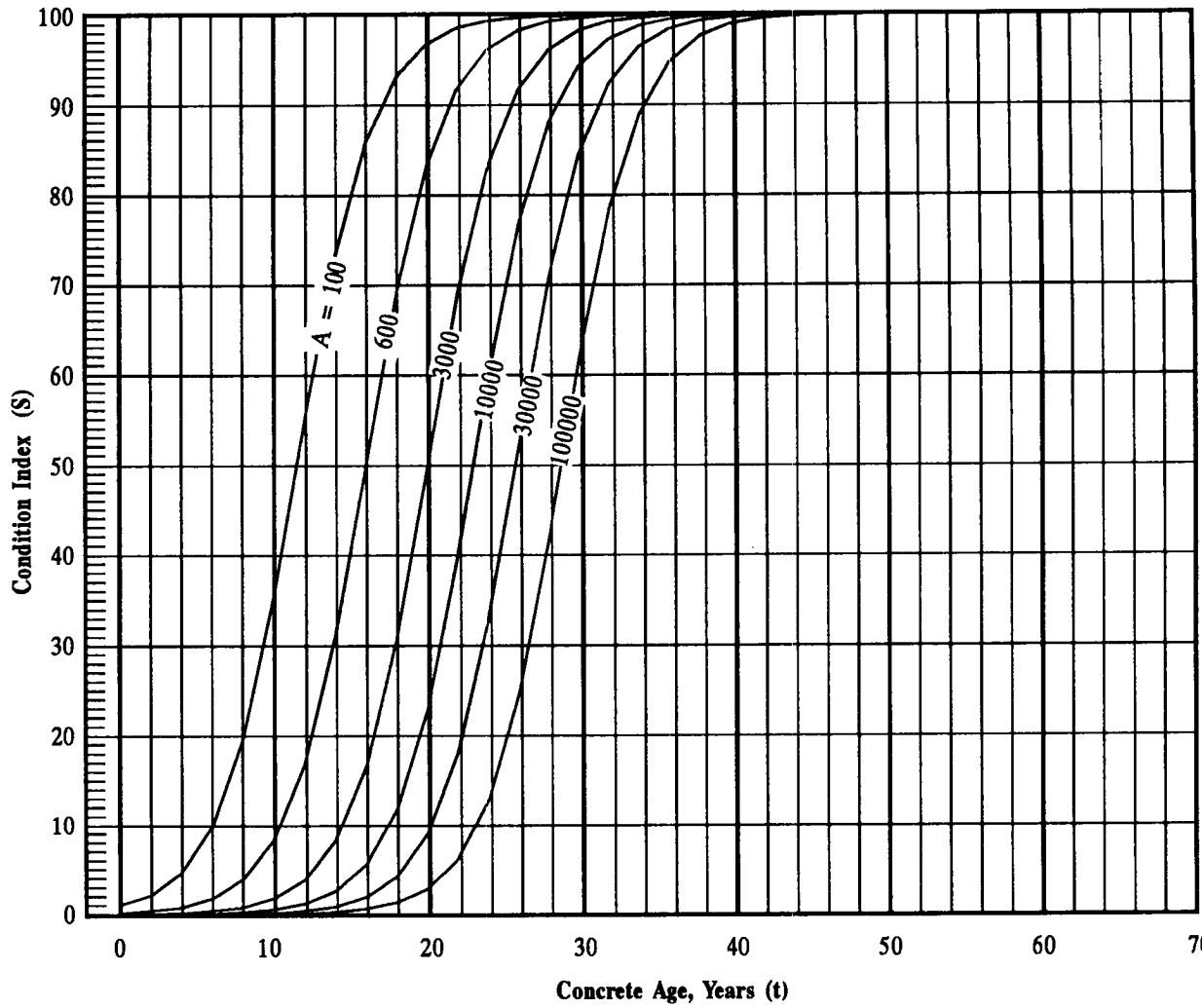
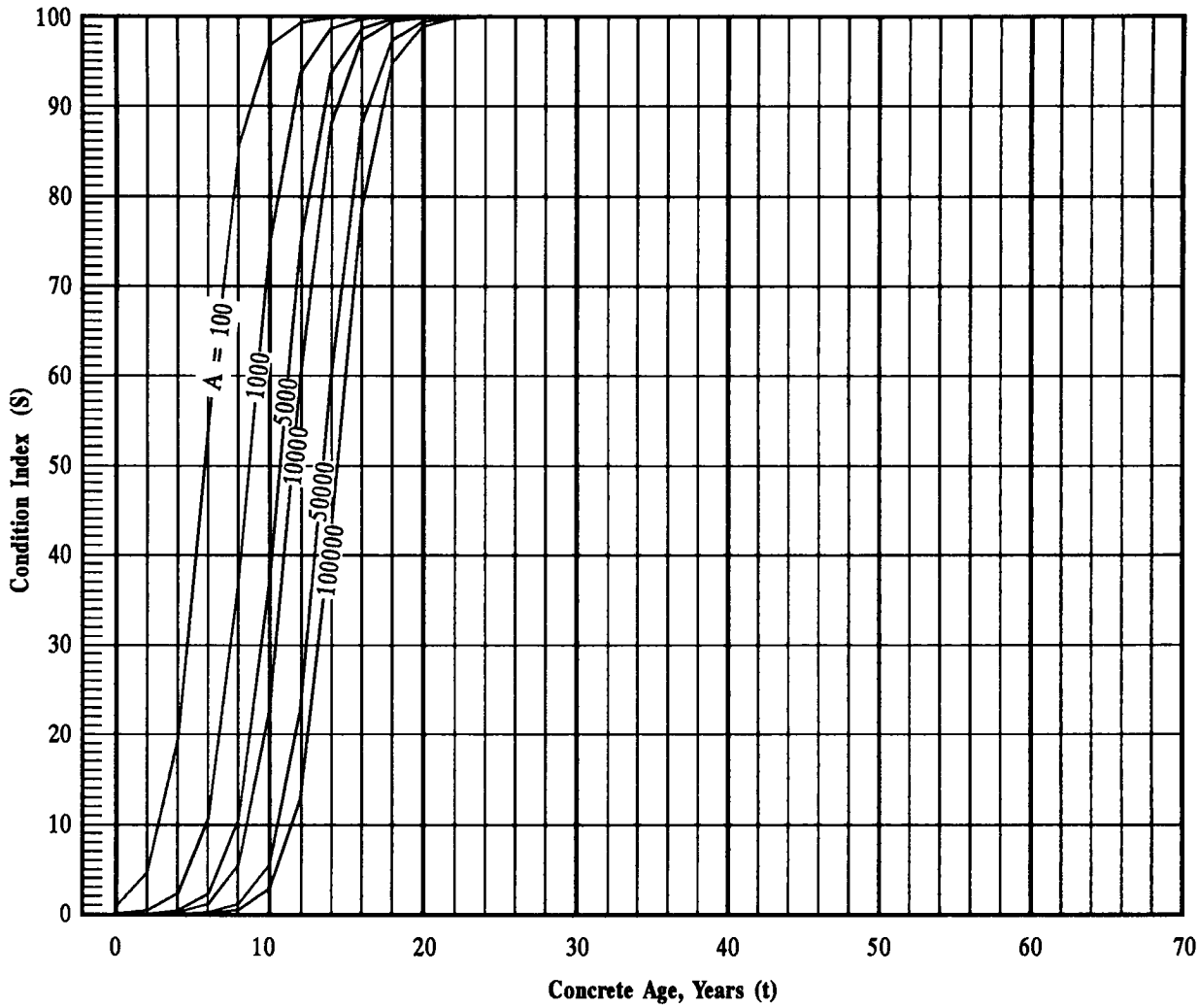


Figure 7.1. (Continued) Concrete Performance Curves, B=.80



8. Compatible Treatment Alternatives

The following sections identify a range of treatment alternatives from which the selection can be made. Generally, there are two types of treatment, deck treatment and structural treatment. Structural treatment, as defined here, applies only to superstructure and substructure elements (i.e., non-deck elements). A comprehensive description of concrete treatment alternatives is provided in SHRP research by Weyers et al.[4]

8.1 Deck Repair

Concrete Patches, Chloride Contaminated Concrete Left in Place

In this procedures deteriorated concrete is removed to the depth required and replaced with concrete.

- Conventional Concrete Patches
- Quick-Set Hydraulic Concrete Patches
- Polymer Concrete Patches

8.2 Deck Rehabilitation/Protection

Concrete Patches, Chloride-Contaminated Concrete Removed

In this procedure, deteriorated and contaminated concrete are removed to the depth required and replaced with concrete.

- Conventional Concrete Patches
- Quick-Set Hydraulic Concrete Patches
- Polymer Concrete Patches

Corrosion Inhibitor Application

- Corrosion Inhibitor Application

Concrete Overlays

- Conventional Concrete
- Low-Slump Dense Concrete
- Silica Fume Concrete
- Latex-Modified Concrete
- Polymer Concrete

Asphalt Concrete and Waterproofing Membrane Overlays

- Preformed Membrane
- Applied-in-Place Membrane

Sealers and Coatings

- Sealers and Coatings

Cathodic Protection

- Slotted System without Overlay
- Overlaid System

8.3 Structural Repair

Concrete Replacement, Chloride Contaminated Concrete Left in Place

In this procedure, deteriorated concrete is removed to the depth required and replaced with concrete.

- Recasting with Concrete (formwork required)
- Preplacing Dry Aggregate and Grouting (formwork required)
- Spraying-on Concrete (Shotcrete)
- Patching with Trowel-Applied Mortar
  - Conventional Mortar
  - Quick-Set Hydraulic Mortar
  - Polymer Mortar

8.4 Structural Rehabilitation/Protection

Concrete Replacement, Chloride-Contaminated Concrete Removed

In this procedure, deteriorated and contaminated concrete are removed to the depth required and replaced with concrete.

- Recasting with Concrete (formwork required)
- Preplacing Dry Aggregate and Grouting (formwork required)
- Spraying-on Concrete (Shotcrete)
- Patching with Trowel-Applied Mortar
  - Conventional Mortar
  - Quick-Set Hydraulic Mortar
  - Polymer Mortar

Concrete "Covers"

- Spraying-on Concrete (Shotcrete)
- Concrete Jacketing (formwork required)

Sealers and Coatings

- Sealers and Coatings

Cathodic Protection

- Cathodic Protection

8.5 Compatible Treatments

Prior to considering all of the alternatives listed in this chapter for a specific site, the user should be aware that restrictions may prevent certain alternatives at that site. Tables 8.1 and 8.2 should be consulted for deck treatment and structural treatment, respectively, to screen out those treatment alternatives which are not compatible with the concrete because of their technical disadvantages.

Table 8.1. Selection of Compatible Deck Treatment Alternatives

Technical Disadvantage	Conc. Over.	AC Memb.	Seal. Coat.	Cathod. Protect.	Reason
Additional dead load critical	Not Good	Not Good		Not Good[1]	Overlays add to dead load[2].
Active cracks in conc.	Not Good			Not Good[3]	Active cracks reflect through concrete.
Existing overlay on deck		Not Good	Not[4] Good		Removal of old system results in rough surface[5].
Concrete surface scaled		Not Good			Rough concrete surface
Existing slotted cathod. protect.	Not Good				Scarifying concrete damages anodes
Existing polymer injection repair in concrete				Not Good	Insulated bars
Electricity not available				Not Good	Cathodic protection needs electricity
Skid resistance critical			Not Good[6]		Skid resistance may decrease
Steep grades and/or crossfalls	Not Good[7]				Concrete may flow after strike off
Sharp skew and/or curvature	Not Good				Difficult to pave with concrete finishing machines

1. When cathodic protection is used with an overlay.
2. Unless, an existing overlay (or a layer of the concrete) is removed and replaced.
3. When cathodic protection is used with a concrete overlay.
4. May be applied on some concrete overlays.
5. Rough concrete surface can puncture membranes, unless a smooth concrete surface can be provided for the new membrane.
6. Exceptions can exist.
7. When slump is 4.5 inches (11.4 centimeters) or more.

Table 8.2 Selection of Compatible Structural Treatment Alternatives

Technical Disadvantage	Recast.	Preplaced Aggregate	Patch	Shot-crete	Cathod. Protect.	Reason
Repair depth more than 2 inches			Not Good	Not[1] Good		Concrete consolidation and bonding can be a problem
Small area repair				Not Good		Mobilization not justified
Internal vibration problem	Not Good					Concrete consolidation can be a problem
Experienced contractor not available		Not Good				Certain skills required
Electricity not available					Not Good	Cathodic Protection need electricity
Existing polymer injection repair in concrete					Not Good	Insulated bars

1. Shotcrete may be applied in several stages.

9. Cost Items Associated with Treatment (Agency Costs)

Costs associated with various treatments should be known in order to select the most cost-effective alternative and determine its timing. Costs can vary significantly from one area to another and from time to time, depending on many factors. The user generally has the most reliable information regarding the cost of a certain treatment in a given jurisdiction.

However, before the user arrives at any cost for a treatment, the standard cost items associated with that treatment must be identified. This chapter of the handbook provides standard highway agency cost items associated with each treatment included in the handbook (Chapter 8). User cost items are discussed in Chapter 10.

The user should determine the cost of each item separately for the treatment considered and then total those itemized costs. Users with no previous experience with the cost of the items outlined in this chapter may consult SHRP research by Weyers et al.[4] and by Bennett, et al.[5]

The user may of course, change treatment procedures outlined here to suit agency policies and practices.

9.1 Cost Items Associated with Applying Deck Treatments

Concrete Patches

Cost items in this category are as follows:

- Removing contaminated and/or deteriorated concrete.
- Patching with concrete and curing.
- Traffic control, when bridge is partially open to traffic.

Cost items in this category should be expressed in terms of dollars per cubic yard of patches, or dollars per square foot of patches, if the depth of the patch is taken into consideration.

Corrosion Inhibitor Application

Cost items in this category are as follows:

- Applying corrosion inhibitor.
  - **When there is <u>not</u> an existing overlay;** spray the inhibitor to soak into the concrete.
  - **When there is an existing overlay**; this treatment may not be considered.
- Traffic control, when the bridge is partially open to traffic.

Cost items in this category should be expressed in terms of dollars per square foot of deck area.

Concrete Overlays

Cost items in this category are as follows:

- Surface preparation.
  - **When there is <u>not</u> an existing overlay;** scarify the concrete surface (sand- or shotblasting for polymer concrete).
  - **When there is an existing overlay;** remove the existing overlay.
- Placing and curing concrete.
- Traffic control, when the bridge is partially open to traffic.

Cost items in this category should be expressed in terms of dollars per square foot of deck area.

Asphalt Concrete and Waterproofing Membrane Overlays

Cost items in this category are as follows:

- Surface preparation.
  - **When there is <u>not</u> an existing overlay;** sandblast the concrete surface.
  - **When there is an existing overlay;** this treatment may not be viable, since removing the existing overlay will result in a rough surface (see Table 8.1 for further information).
- Placing membrane.
- Placing asphalt concrete.
- Traffic control, when the bridge is partially open to traffic.

Cost items in this category should be expressed in terms of dollars per square foot of deck area.

Sealers and Coatings

Cost items in this category are as follows:

- Surface preparation.
  - **When there is <u>not</u> an existing overlay;** sandblast the concrete surface.
  - **When there is an existing overlay;** this treatment may not be used, since sealers are generally not applied on special concrete overlays or on asphalt concrete surfaces; if the existing overlay is removed, it will result in a rough surface (see Table 8.1 for further information).
- Applying sealer or coating.
- Traffic control, when the bridge is partially open to traffic.

Cost items in this category should be expressed in terms of dollars per square foot of deck area.

Cathodic Protection, Slotted System

Cost items in this category are as follows:

- Surface preparation.
  - **When there is a concrete surface;** saw cut slots.
  - **When there is an existing di-electric overlay (e.g., asphalt concrete/membrane, or polymer concrete);** this treatment is not recommended, since removing the existing overlay will result in a rough surface.
- Placing wire anodes in slots.
  - Placing electrically conductive polymer in slots.
  - Traffic control, when the bridge is partially open to traffic.

Cost items in this category should be expressed in terms of dollars per square foot of deck area.

Cathodic Protection, Overlaid System

Cost items in this category are as follows:

- Surface preparation.
  - **When there is <u>not</u> an existing overlay;** Scarify the concrete surface.
  - **When there is an existing overlay**; remove the existing overlay.
- Attaching of mesh anodes to the surface.
- Placing, and curing concrete overlay.
- Traffic control, when the bridge is partially open to traffic.

Cost items in this category should be expressed in terms of dollars per square foot of deck area.

9.2 Cost Items Associated with Applying Structural Treatments

Concrete Replacement

Cost items in this category are as follows:

- Removing contaminated and/or deteriorated concrete.
- Formwork (formwork is not required for shotcrete and patching)
- Placing and curing concrete.
- Traffic control, when the bridge is partially open to traffic.

Cost items in this category should be expressed in terms of dollars per cubic yard of replacement, or dollars per square foot of replacement, if the depth of the patch is taken into consideration.

Concrete "Covers"

Cost items in this category are as follows:

- Surface preparation (sandblasting).
- Formwork (form work is not required for shotcrete)
- Placing and curing concrete.
- Traffic control, when the bridge is partially open to traffic.

Cost items in this category should be expressed in terms of dollars per square feet of concrete area treated.

Sealers and Coatings

Cost items in this category are as follows:

- Surface preparation (sandblasting).
- Applying sealer or coating.
- Traffic control, when bridge is partially open to traffic.

Cost items in this category should be expressed in terms of dollars per square foot of concrete area treated.

Cathodic Protection

Cost items in this category are as follows:

- Surface preparation (sandblasting).
- Attaching mesh anodes to the surface.
- Placing and curing protective mortar (shotcrete).
- Traffic control, when the bridge is partially open to traffic.

Cost items in this category should be expressed in terms of dollars per square foot of concrete area treated.

9.3 Cost Item Associated with Monitoring and Maintaining Treatment

Certain treatments may require periodic costs of monitoring and/or maintaining the treatment. For example, cathodic protection installations need to be periodically monitored for the polarized steel potentials, regardless of the age of the system, to maintain the potentials within the prescribed limits.

10. Cost Items Associated with Treatment (User Costs)

Two types of user costs are included in the methodology. Those are: (1) during-treatment costs, and (2) prior-to-treatment costs.

10.1 During-Treatment Costs

Costs during the treatment are related to increases in travel time caused by traffic congestion on the bridge, or by a detour around the bridge during bridge closure. Use the equation given below, or Figure 10.1, to find the user costs resulting from the degree of bridge closure.

$$U_1 = K_1 \, t_t \, t_c \, q_o \qquad \text{(Equation 10.1)}$$

where:

U_1 = user costs during the treatment period, dollars

K_1 = value of bridge user time while traveling, dollars per minute per vehicle

t_c = duration of treatment, days

q_o = average two-way daily traffic volume across the bridge, vehicles per day

t_t = increment in travel time across the bridge (or in detour around the bridge) caused by construction, minutes

For traveling across the bridge, t_t may be obtained from Equation 10.2 or Figure 10.2.

$$t_t = 0.15 \, t_f \, [(q_o / C1)^4 - (q_o / C)^4] \qquad \text{(Equation 10.2)}$$

where

t_f = free-flow travel time across the bridge, minutes

C1 = two-way capacity of the bridge during construction, vehicles per day

C = two-way capacity of the bridge during normal periods, vehicles per day

10.2 Prior-to-Treatment Costs (Decks Only)

Costs in the period prior to treatment are a function of the condition of the bridge deck and its effect on traffic flow. A badly spalled deck would impede traffic flow, causing speed reductions, congestion, and resulting increase in travel time and cost. Use the following equation, or Figure 10.3, to find user costs due to worsening deck condition for a given year.

$$U_2 = K_2 [S / S_m]^4 [365 q_o] \qquad \text{(Equation 10.3)}$$

where

U_2 = user costs due to worsening deck condition, dollars per year

K_2 = a calibrating constant, dollars per vehicle

[$K_2 = a\ t_f\ K_1$: See "During-Treatment Costs" for definitions of K_1 and t_f. Parameter "a" is the percentage of free-flow travel time, t_f, representing the increment in travel time when $S = S_m$.]

S = concrete condition index for the year considered (Chapter 6)

S_m = maximum tolerable condition index (Chapter 5)

q_o = average two-way daily traffic volume across the bridge, vehicles per day

Figure 10.1. Nomogram for User Costs During Treatment

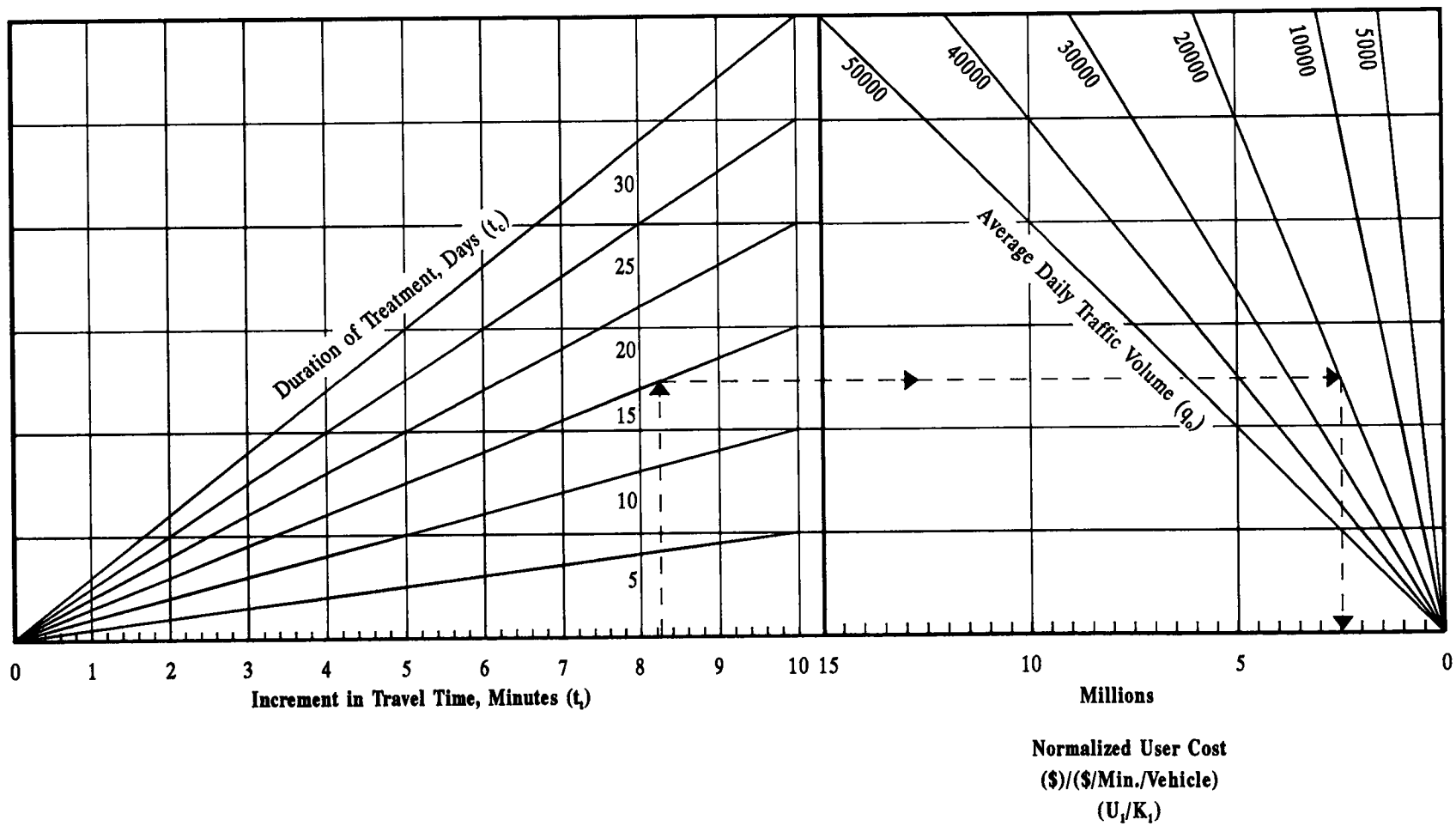


Figure 10.1. (Continued) Nomogram for User Costs During Treatment

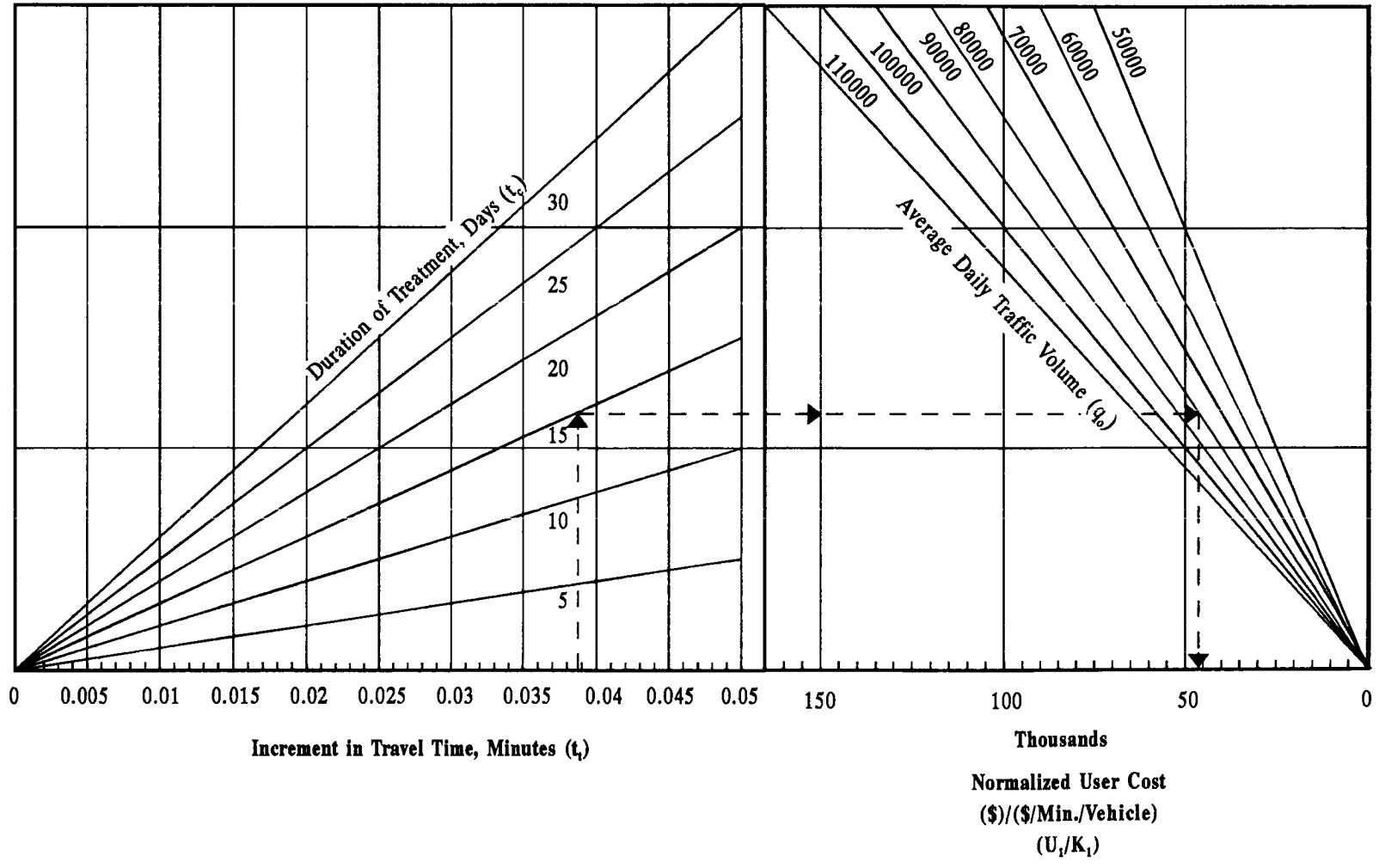


Figure 10.2. Nomogram to Determine Increment in Travel Time Across Bridge

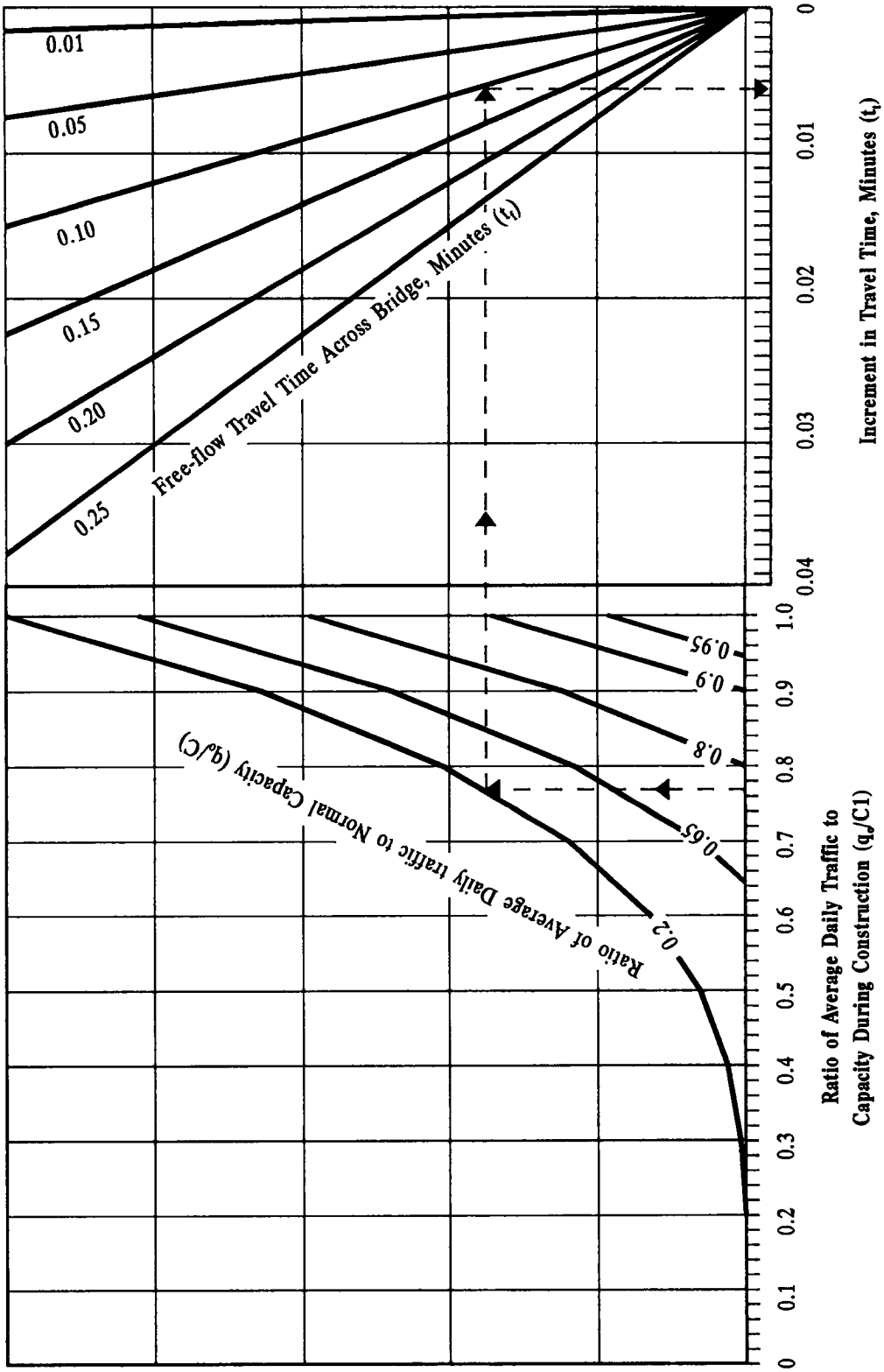
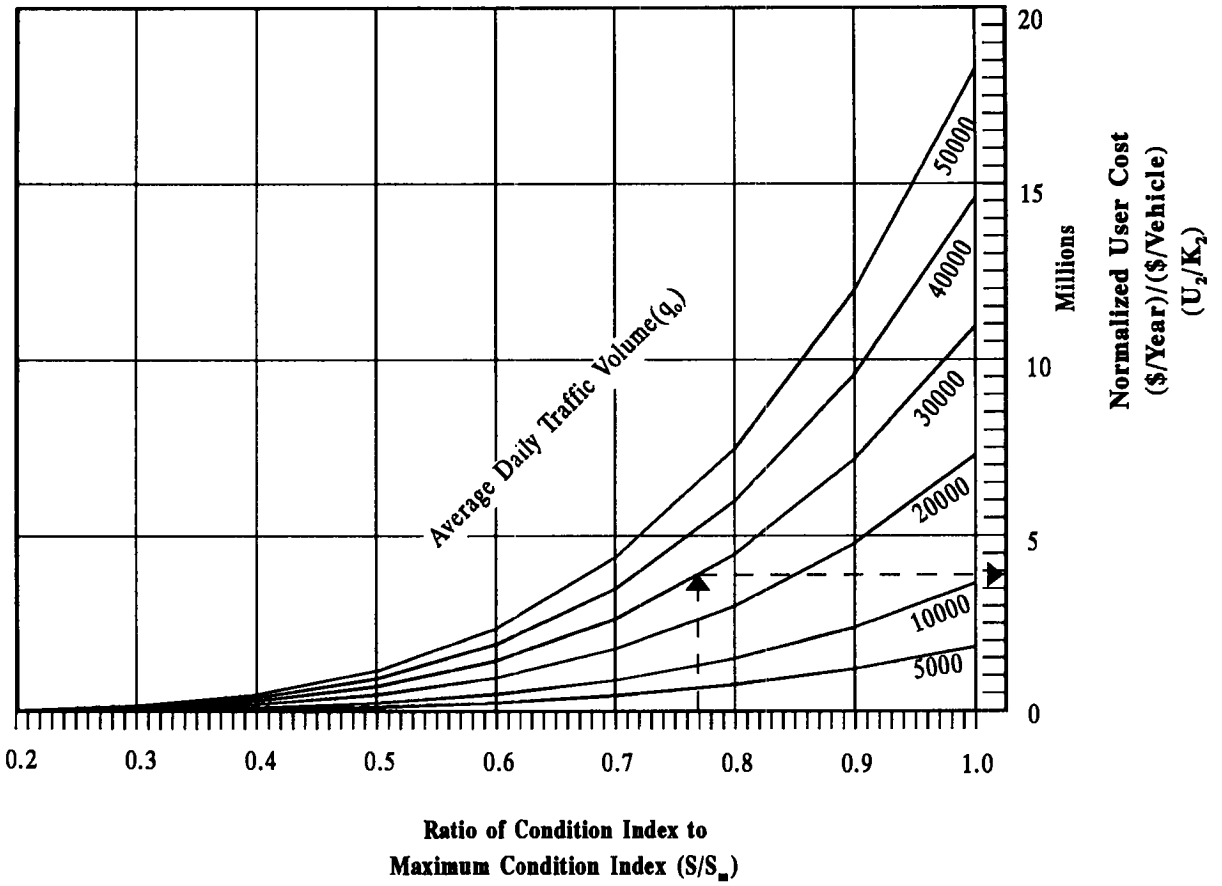


Figure 10.3. Nomogram to Determine User Costs Prior to Treatment



11. Decomposing Concrete Condition Index

In order to estimate agency costs and user costs associated with a treatment (Chapter 9, and 10), the amount of concrete repair (removing and replacing deteriorated and possibly contaminated concrete) needs to be predicted at the time of treatment. The user can predict the amount of deterioration and contamination in the future by decomposing the future concrete condition index, S, into its component parts (i.e., CL, DELAM, and SPALL, see Chapter 5). Use the following procedure to decompose concrete condition index.

11.1 Assumptions

1. Chloride contamination, CL, increases 5 percent for each index increase of one unit.

2. For all deck concrete except those with 1-inch (2.54 centimeters), or thicker, concrete overlays: DELAM is 4 times SPALL. For all deck concrete with 1-inch or thicker, bonded concrete overlays: DELAM is 8 times SPALL.

3. For all non-deck concrete except those with 1-inch (2.54 centimeters), or thicker, concrete jackets or shotcrete: DELAM is 8 times SPALL. For all non-deck concrete with 1-inch (2.54 centimeters), or thicker, concrete jackets or shotcrete: DELAM is 16 times SPALL.

11.2 Procedure (valid only for weighting factors used in Equation 5.1)

$$CL = 5\,S \quad \text{and} \quad CL <= 100 \qquad \text{(Equation 11.1)}$$

$$DELAM = (8.5\,S - CL) / (2.5 + 7.5/N) \qquad \text{(Equation 11.2)}$$

where

N = ratio of DELAM to SPALL, as discussed in the assumptions

$$SPALL = DELAM / N \text{ (DELAM does not include SPALL)} \qquad \text{(Equation 11.3)}$$

12. Prediction of Performance, Treated Concrete

The methodology employs life-cycle cost analysis to determine the cost-effectiveness of a proposed treatment. Therefore, the service life of the treated concrete also needs to be predicted. The aim of this chapter is to predict the effective service life expected of the treated concrete. As defined in this chapter, at the end of the effective service life of the treated concrete the concrete condition index is the maximum tolerable, S_m. Use the following procedures to predict the effective service life of the treated concrete. Apply the same effective service life to the next cycles of treatment.

[It should be noted that in order to achieve the effective service life predicted for the treated concrete in this chapter, the treatment may be repeated, depending on the durability of the treatment itself. This may include reapplying sealers/coatings, removing and replacing overlays, and renewing cathodic protection systems. The user should determine the service life expected of the treatment itself, on the basis of environmental factors. SHRP research by Weyers et al.[4] may be consulted for this purpose.]

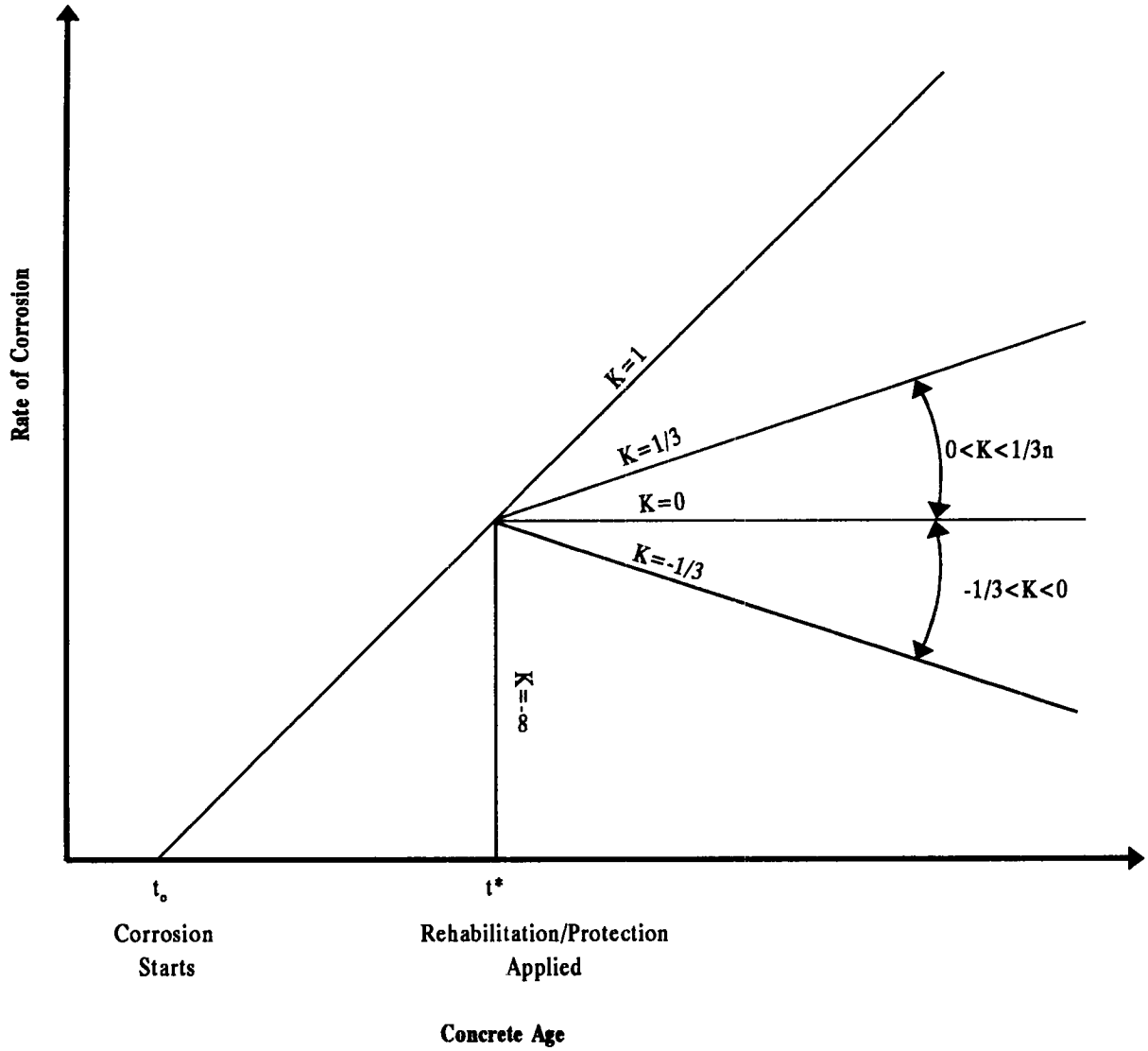
12.1 Case 1: Concrete <u>not</u> Repaired, Rehabilitated, and/or Protected Previously

Case 1 applies to all concretes which will be repaired, rehabilitated, and/or protected for the first time.

Two factors affect the effective service life of the concrete after the treatment. Those are (1) the inherent corrosion mechanism active at the time of treatment, and 2) the treatment's effect on the future corrosion process. Generally, there are five trends in the corrosion process after the treatment, as shown in Figure 12.1 and described below.

1. The rate of corrosion continues to increase at the same rate after the treatment. This condition is represented by K = 1 in Figure 12.1 (typical of only patching when deteriorated concrete is removed and replaced, but contaminated concrete is left in place). Estimate the effective service life of the treated concrete from Equation 12.1 (see Figure 12.1 for derivation of the equation; note that K = 1), or Figure 12.2.

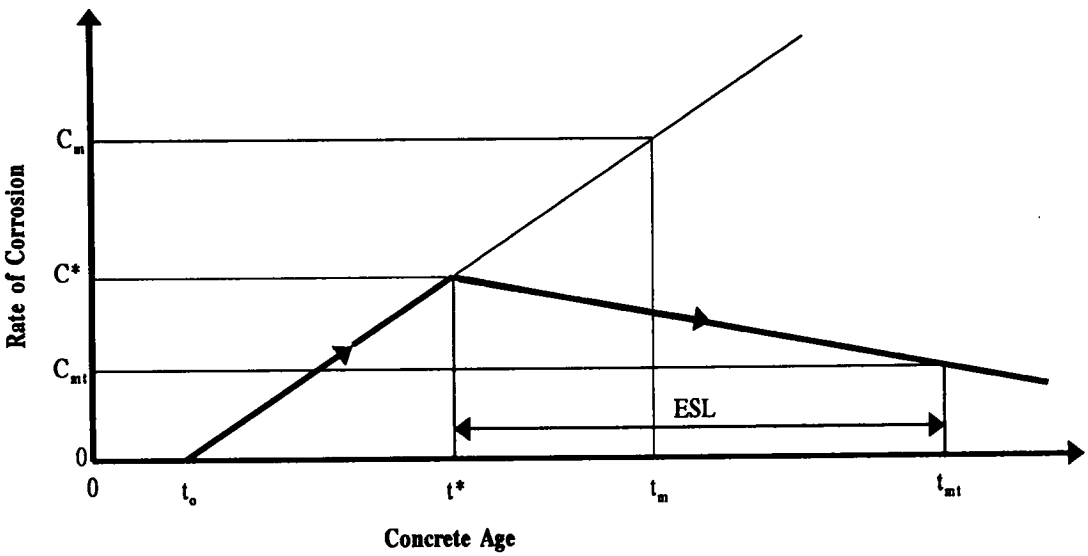
Figure 12.1. Trends of Corrosion Process After Treatment



K = Ratio of Slope of Corrosion Rate Line After Treatment to Slope of Corrosion Rate Line Before Treatment.

Figure 12.1. (Continued) Trends of Corrosion Process After Treatment

Derivation of Equation of Effective Service Life for Concrete not Repaired, Rehabilitated, and/or Protected Previously



Area under rate of corrosion curve from t_o to t_m = 0.5 C_m (t_m - t_o)

Area under rate of corrosion curve from t* to t_{mt} = 0.5 ESL (C* + C_{mt})

Thus:

$$0.5\ C_m (t_m - t_o) = 0.5\ ESL\ (C^* + C_{mt}) \quad (1)$$

Where:

$$C^* = C_m (t^* - t_o) / (t_m - t_o), \text{ and} \quad (2)$$

$$C_{mt} = C^* [1 + K\ (ESL) / (t^* - t_o)] \quad (3)$$

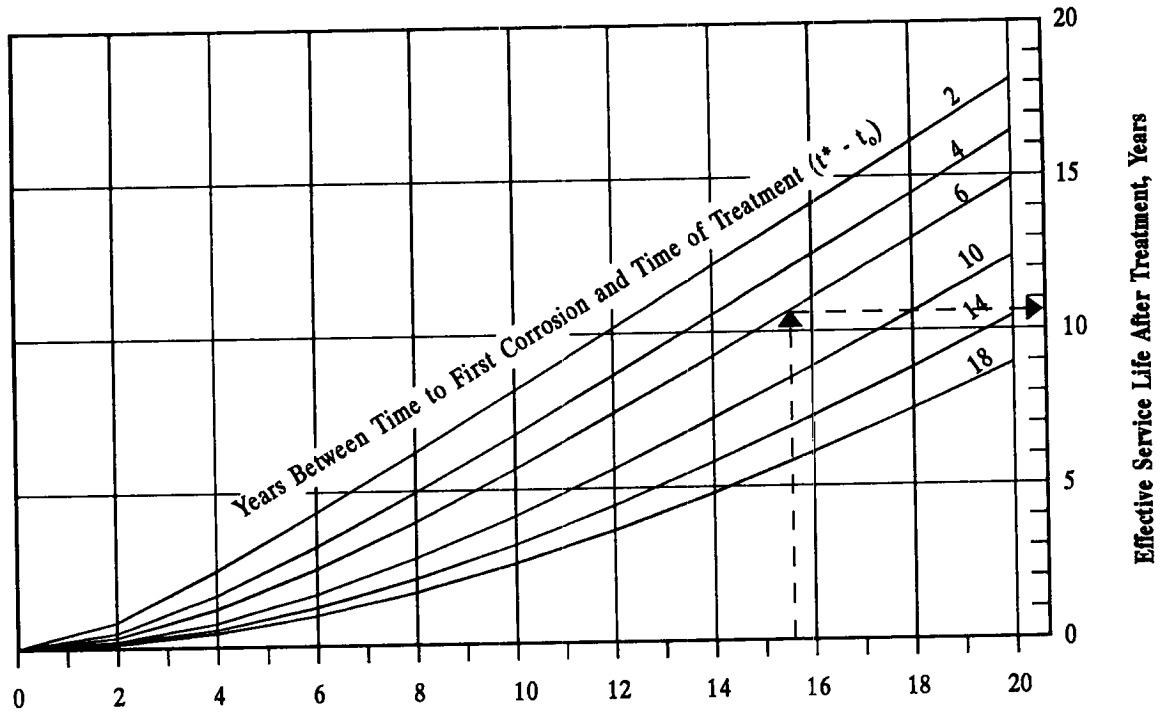
Substituting (2) and (3) in (1) will give:

$$K\ (ESL)^2 + 2\ (t^* - t_o)\ (ESL) - (t_m - t_o)^2 = 0 \quad (4)$$

Solving (4) will give ESL as:

$$ESL = \{[(t^* - t_o)^2 + K(t_m - t_o)^2]^{0.5} - (t^* - t_o)\}/K$$

Figure 12.2. Nomogram to Determine Effective Service Life of Concrete After Treatment When Rate of Corrosion Continues at the Same Rate K = 1



$$ESL = [(t^* - t_o)^2 + (t_m - t_o)^2]^{0.5} - (t^* - t_o) \quad \text{(Equation 12.1)}$$

where

ESL = effective service life, years

t^* = age of concrete at time of treatment, years

t_m = age of concrete at condition index of S_m, if the concrete was not treated (Chapter 7), years

t_o = age of concrete at time to first sign of corrosion, years (Find t_d, time to first sign of deterioration from Chapter 6. Enter Figure 12.3 with t_d and determine t_o.)

2. The rate of corrosion increases gradually after the treatment, but at a slower rate. This condition is represented by $0<K<1/3$ in Figure 12.1 (typical of sealers, coatings, and asphalt concrete/membrane systems). Estimate the effective service life of the treated concrete from Equation 12.2 (see Figure 12.1 for derivation of the equation), or Figure 12.4.

$$ESL = \{[(t^* - t_o)^2 + K(t_m - t_o)^2]^{0.5} - (t^* - t_o)\} / K \quad \text{(Equation 12.2)}$$

where

K = the ratio of the slope of corrosion rate increase after treatment to the slope of corrosion rate increase before treatment ($0<K<1/3$).

See 1., above, for the definition of the other parameters in Equation 12.2.

3. The rate of corrosion levels off after the treatment. This condition is represented by K = 0 in Figure 12.1 (typical of asphalt concrete/membrane systems, sealers, and coatings at their best performance; or concrete overlays at their worst performance). Estimate the effective service life of the treated concrete from Equation 12.3 (see Figure 12.1 for derivation of the equation; note that K = 0), or Figure 12.5.

$$ESL = 0.5 (t_m - t_o)^2 / (t^* - t_o) \quad \text{(Equation 12.3)}$$

Figure 12.3. Chart to Find Age of Concrete at Time of First Corrosion

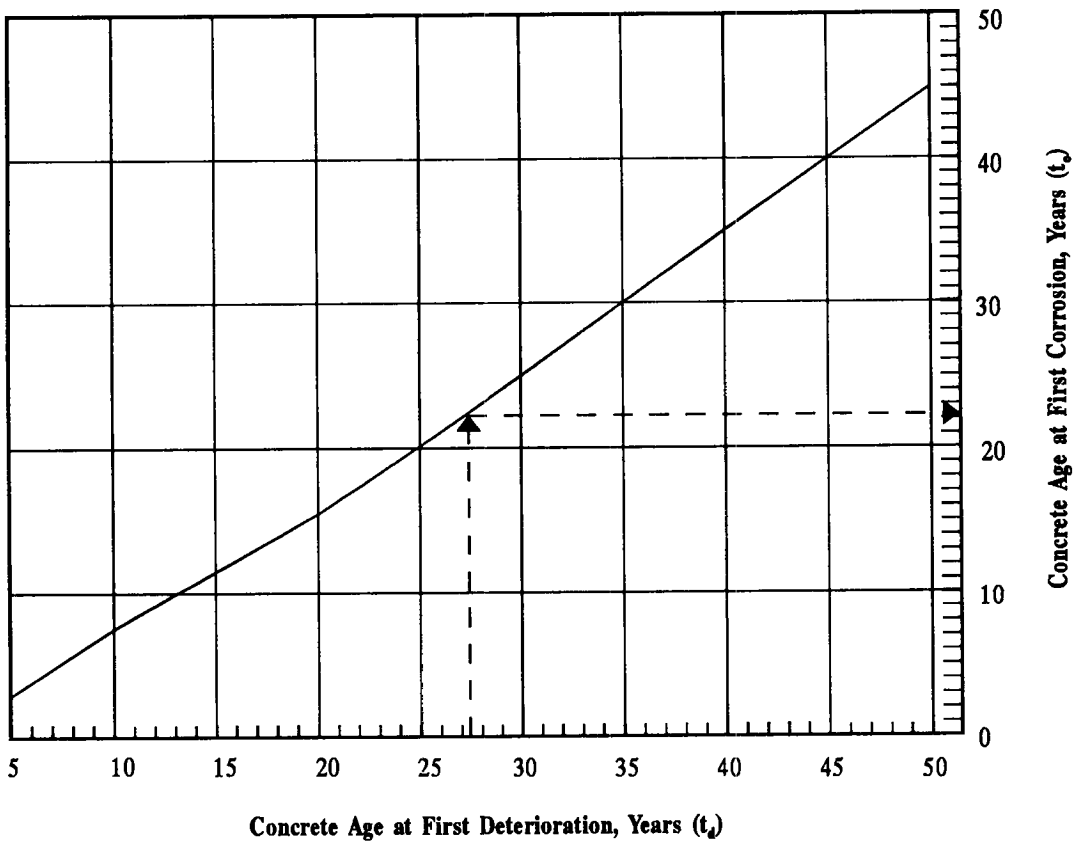


Figure 12.4. Nomogram to Determine Effective Service Life of Concrete After Treatment When Rate of Corrosion Increases at a Slower Rate (0<K<1/3)

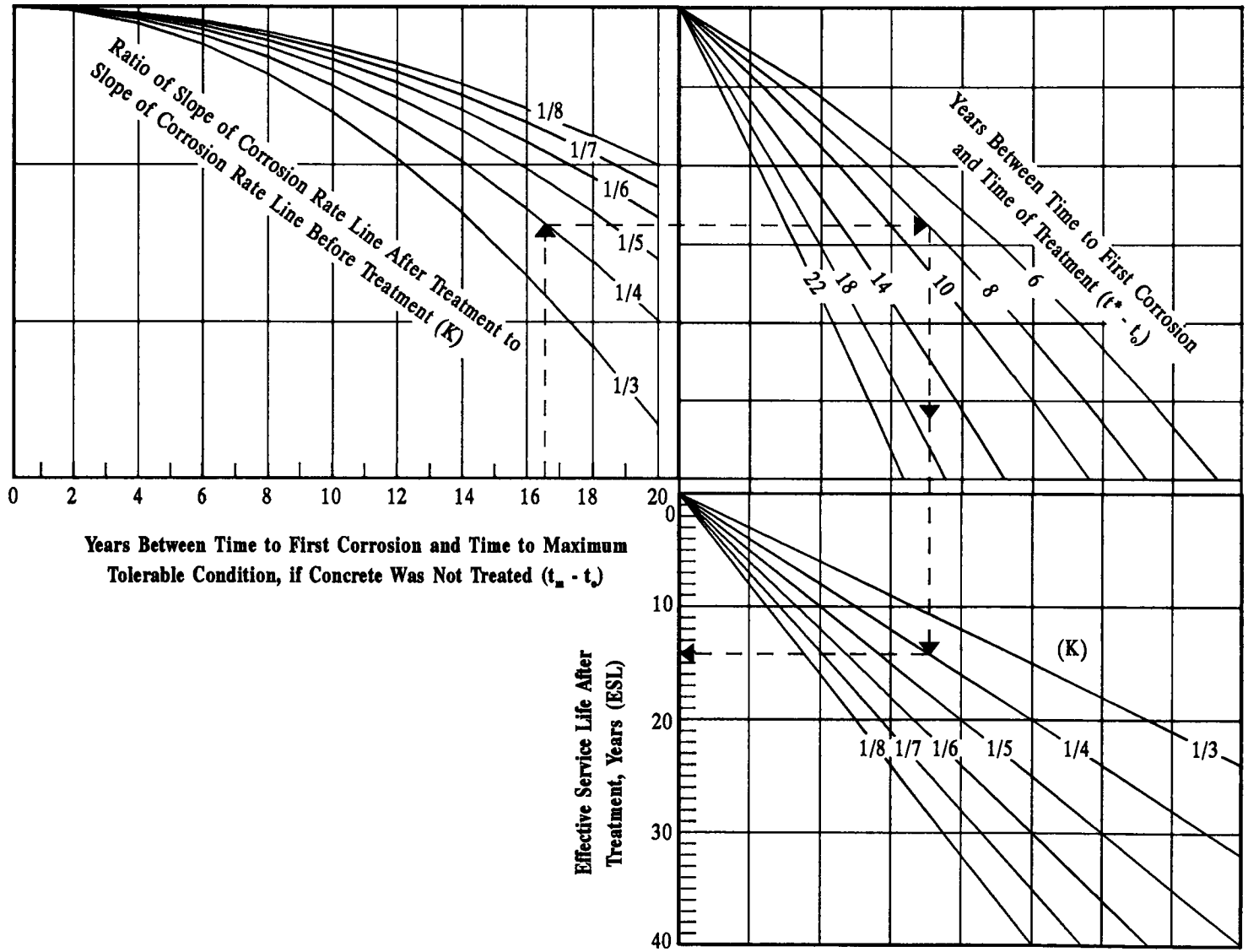
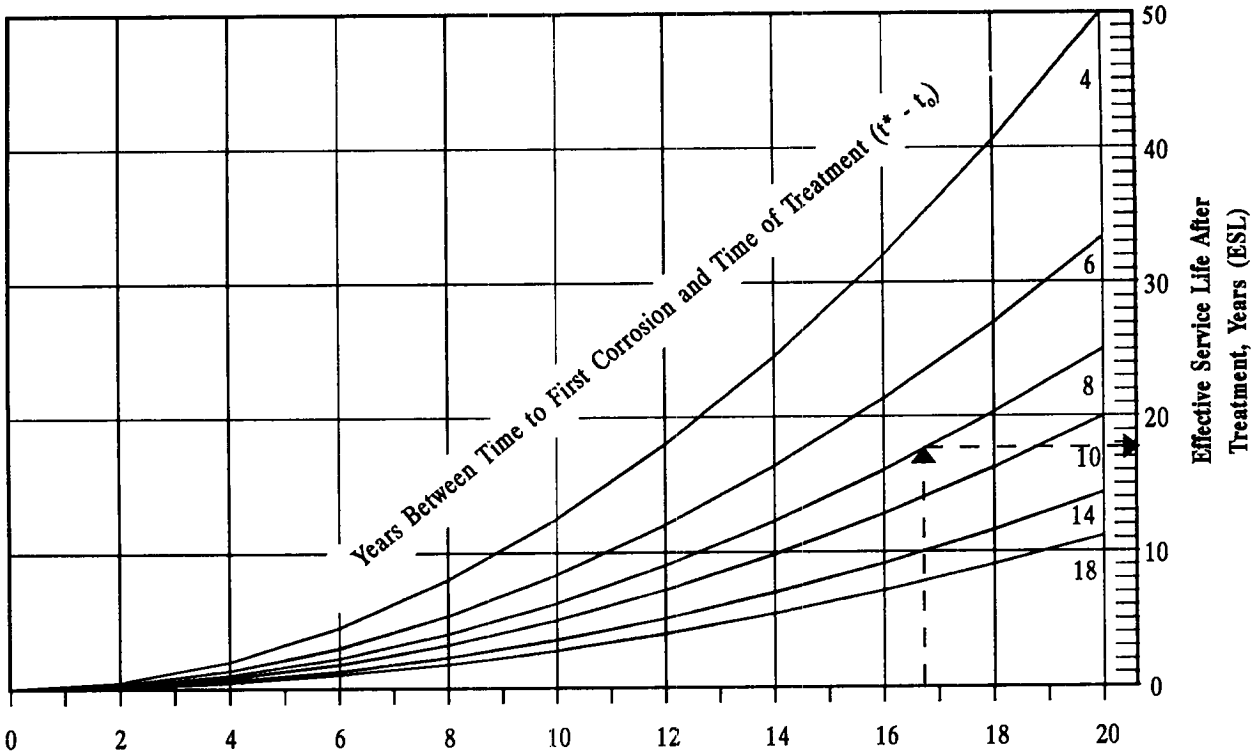


Figure 12.5. Nomogram to Determine Effective Service Life of Concrete After Treatment When Rate of Corrosion Levels Off (K = 0)



See 1., above, for the definition of the parameters in Equation 12.3.

4. The rate of corrosion decreases gradually after the treatment. This condition is represented by $-1/3 < K < 0$ (typical of concrete overlays). Estimate the effective service life of the treated concrete from Equation 12.4 (see Figure 12.1 for derivation of the equation), or Figure 12.6.

$$ESL = \{[(t^* - t_o)^2 + K(t_m - t_o)^2]^{0.5} - (t^* - t_o)\} / K \qquad \text{(Equation 12.4)}$$

where

K = the ratio of the slope of corrosion rate decrease after treatment to the slope of corrosion rate increase before treatment ($-1/3 < K < 0$)

See 1., above, for the definition of the other parameters in the Equation 12.4.

If $K < -(t^* - t_o)^2 / (t_m - t_o)^2$, then ESL is theoretically infinite. This means that the corrosion rate of the treated concrete drops to zero when the condition index is still less than the maximum tolerable condition index, S_m. Thus, the condition index will theoretically never reach the maximum tolerable.

5. The rate of corrosion drops to 0 after the treatment. This condition is represented by K = infinite in Figure 12.1 (typical of cathodic protection at its best performance, or removal of all contaminated concrete and protection against further chloride intrusion). The effective service life of the treated concrete in this case is theoretically infinite, provided the protection is repeated periodically, as needed to keep the concrete free of corrosion.

12.2 Case 2: Concrete Repaired, Rehabilitated and/or Protected Previously

Case 2 applies to all concretes which were previously repaired, rehabilitated, and/or protected and will be repaired, rehabilitated, and/or protected again. Use the following procedure to predict the effective service life of the treated concrete.

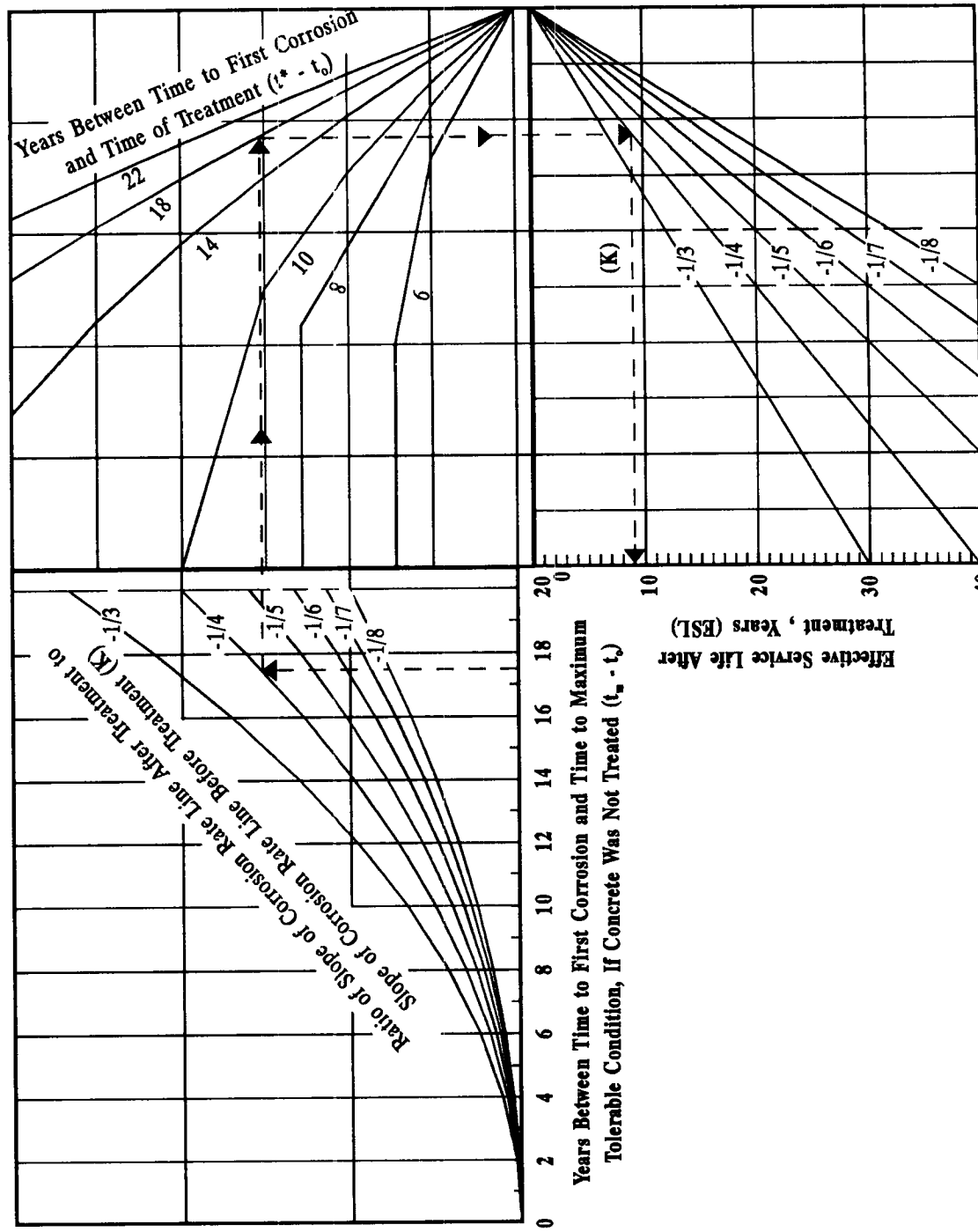


Figure 12.6. Nomogram to Determine Effective Service Life of Concrete After Treatment When Rate of Corrosion Decreases (-1/3<K<0)

Step 1

Find t_p, age of concrete at present, years, and C_p, the rate of corrosion at present, milli-amperes per square foot. C_p is the 90th percentile value (i.e., average rate of corrosion plus 1.282 standard deviation).

Step 2

Find t_r, age of concrete at the time of the previous repair, rehabilitation, and/or protection, years; find C_r, the rate of corrosion at the time of the previous repair, rehabilitation, and/or protection, milli-amperes per square foot. If C_r is not known, use the following procedure to estimate C_r.

- If a sealer/coating, an asphalt concrete-membrane system, or a concrete overlay was previously installed, the corrosion rate has almost remained constant. In this case, assume $C_r = C_p$.

- If none of the above systems was installed, assume C_r is equal to the greater of the following.

  1 mA/sq. ft (10.8 mA/sq. m), or $(C_p)(S_r)/(S_p)$

in which:

S_r = concrete condition index just after previous repair, rehabilitation, and/or protection

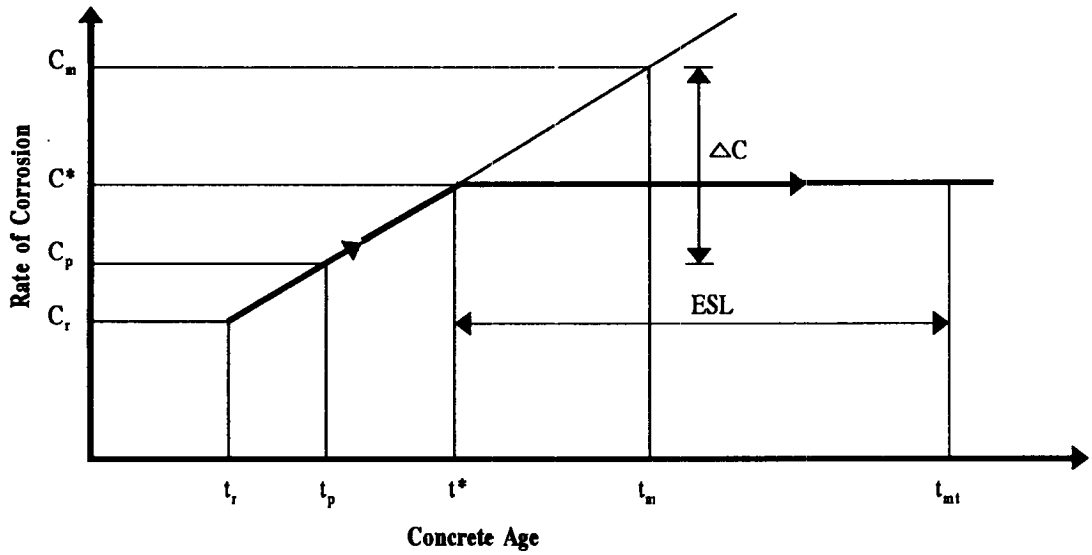
S_p = concrete condition index when C_p is measured

Step 3

Find t_m, age of the previously repaired, rehabilitated, and/or protected concrete at condition index of S_m (maximum tolerable), years, (Chapter 7) assuming no new repair, rehabilitation, and/or protection is applied. Then use Equation 12.5 to estimate C_m, the rate of corrosion corresponding to t_m, milli-amperes per square foot. (see Figure 12.7 for derivation of Equation 12.5).

$$C_m = [C_p (t_m - t_r) - C_r (t_m - t_p)] / (t_p - t_r) \qquad \text{(Equation 12.5)}$$

Figure 12.7. Trend of Corrosion Process After Treatment (Concrete Repaired, Rehabilitated, and/or Protected Previously)



Derivation of Equation for C_m

$C_m = C_p + \triangle C$

$$\triangle C = \frac{(t_m - t_p)(C_m - C_r)}{(t_m - t_p)}$$

Then:

$C_m = [C_p (t_m - t_r) - C_r(t_m - t_p)] / (t_p - t_r)$

Derivation of Equation for ESL

Area under rate of corrosion curve from t_r to t_m $= 0.5(C_m + C_r)(t_m - t_r)$

Area under rate of corrosion curve from t^* to t_{mt} $= (C^*)(ESL)$

Thus:

$0.5 (C_m + C_r)(t_m - t_r) = (C^*)(ESL)$

and

$ESL = [(C_m + C_r)(t_m - t_r)] / (2C^*)$

Step 4

Use Equation 12.6 to estimate C^*, the rate of corrosion corresponding to t^* (age of concrete at time of treatment, years), milli-amperes per square foot (change t_m to t^* in Equation 12.5 to obtain Equation 12.6).

$$C^* = [C_p (t^* - t_r) - C_r (t^* - t_p)] / (t_p - t_r) \quad \text{(Equation 12.6)}$$

Step 5

Estimate the effective service life of the newly treated concrete (ESL), years, from Equation 12.7, assuming the rate of corrosion after the treatment will roughly remain constant (a behavior generally expected of sealers/coatings, asphalt concrete-membrane systems, or rigid overlays. See Figure 12.7 for the derivation of Equation 12.7).

$$ESL = [C_m + C_r) (t_m - t_r)] / (2 C^*) \quad \text{(Equation 12.7)}$$

Note that if the concrete was also previously treated with sealers/coatings, asphalt concrete-membrane systems, or rigid overlays, in the absence of background rate of corrosion data, it may be assumed

$$C_m = C_r = C^*$$

and Equation 12.7 will give

$$ESL = t_m - t_r \quad \text{(Equation 12.8)}$$

For more accuracy, users may adjust the effective service life obtained from Equation 12.8, when the new treatment is not the same as the previous treatment. The adjustment should be on the basis of the experience and/or the results of SHRP research by Weyers et al.[4] As a default, the effective service life obtained from Equation 12.8 may be increased 30 percent if the new treatment is a concrete overlay and the previous treatment was a sealer/coating or asphalt concrete-membrane system. On the other hand, the effective service life may be decreased 25 percent if the new treatment is a sealer/coating or asphalt concrete-membrane system and the previous treatment was a concrete overlay.

12.2 Case 3: Preventive Treatment

Case 3 applies to concretes which are not chloride contaminated at the bar level and which will receive protection against further contamination immediately. Under this condition, the bar-level chloride content is equal to, or less than, the corrosion threshold. Although corrosion is not present, any existing surface chlorides, can diffuse into the

concrete later and cause bar corrosion after the treatment. Use the following procedure to predict the effective service life of the concrete after preventive treatment.

Step 1

Determine the set of data corresponding to the first signs of deterioration after the treatment, as shown below.

t_d = age of the concrete at time to first deterioration, years (Use Equation 12.9 to find t_d).

$$t_d = (2.695\ d^{1.22}) / (Z_t^{0.42}\ P) \qquad \text{(Equation 12.9)}$$

See Equation 6.2 for definition of the parameters in Equation 12.9.

S_d = condition Index at time to first deterioration, 1.9

Step 2

Determine the set of data corresponding to the condition index equal to 45 after the treatment, as shown below.

t_{45} = age of the concrete at condition index of 45, years, determined from Table 6.1 based on the average wet resistivity of the concrete surrounding the reinforcing steel

S_{45} = condition index of 45

Step 3

Use the following equations to calculate Parameters A and B in the performance equation of the treated concrete. Alternatively, use Figures 6.3 and 6.4 to find B and A, respectively.

$$B = \ln\{[S_d(100 - S_{45})] / [S_{45}(100 - S_d)]\} / (t_d - t_{45}) \qquad \text{(Equation 6.6)}$$

$$A = [(100 - S_{45}) / S_{45}] / [\exp(-Bt_{45})] \qquad \text{(Equation 6.7)}$$

Step 4

Find the performance curve corresponding to Parameters A and B in Figure 7.1. Enter the performance curve with S equal to S_m and find t_m, the age of the concrete at the time

of the maximum tolerable condition index, years. The effective service life of the concrete after the treatment is t_m - t_p in which t_p is the age of concrete at present, years.

13. Optimum Treatment and Time of Treatment

Having determined in previous chapters (1) the concrete performance, (2) "treatment consideration period," (3) compatible treatment alternatives, (4) how to determine costs associated with a treatment, and (5) the performance after the treatment, the user must decide what type of treatment to apply, and when to apply it within the treatment consideration period, for maximum cost-effectiveness. This chapter deals with this subject through life-cycle cost analysis. Briefly, this chapter will first determine the optimum time of treatment, for each compatible treatment; subsequently, it will compare the corresponding life-cycle costs in order to prioritize the compatible treatments. These procedures are discussed below.

For simplicity, for a compatible treatment, the user of the handbook will consider treating the concrete at only three different points in time for comparison:

1. Present time (Concrete Age = t_p; Index = S_p)

2. Time corresponding to maximum tolerable condition index (Concrete Age = t_m; Index = S_m)

3. Time between t_p and t_m (Concrete Age = $(t_p + t_m)/2$; Index = $S_{p\text{-}m}$).

For the purpose of life-cycle cost comparison only, the user may also assume concrete treated at a point in time in the past and use the same procedure outlined in this chapter to determine the corresponding life-cycle cost.

In this handbook, the economic analysis of the three possible strategies described above will be done within a set time frame called the "planning horizon." The planning horizon begins with the present time and extends for 20 years. However, if the service life of the component considered for treatment is limited due to the functional features of the bridge, the planning horizon will be the remaining service life of the structure (see Chapter 3 for details).

For simplicity, this methodology assumes that after the initial treatment the concrete will only be treated when its condition index has reached S_m (maximum tolerable). This assumption is justified for two reasons: (1) when costs are discounted, the timing of the

costs that occur far in the future do not significantly affect the life-cycle cost, and (2) when concrete is treated and protected positively, the most cost effective strategy is logically the one that gets the maximum possible use out of the treatment.

All costs associated with each strategy, including costs of repeated cycles of treatment within the planning horizon (agency costs and user costs), and salvage value of the last cycle of treatment, are then discounted and totaled for comparison with the other strategies. At the end of this economic analysis, the user will be able to determine the optimum strategy, time of treatment for a compatible treatment. Also, the user will be able to prioritize the various compatible treatments, based on their life-cycle costs. Detailed procedures are described in the following sections.

13.1 Life-Cycle Cost of a Selected Treatment and Strategy

For a selected compatible treatment and a selected strategy, the life-cycle cost can be estimated by tabulating the strategy in the worksheet shown in Figure 13.1. Figures 13.2, 13.3, and 13.4 are examples of tabulated strategies of "treat at t_p", "treat at t_m", and "treat between t_p and t_m", respectively. To estimate each strategy's life-cycle cost, use the following step-by-step procedure to tabulate the three strategies for a selected compatible treatment in Figure 13.1.

Step 1 (Planning Horizon)

Columns 1 and 2 correspond to the 20-year planning horizon. Fill out Column 1 by starting with the present date in the first row (1992). Fill out Column 2 by starting with Year 1 in the first row (i.e., 1).

Step 2 (Condition Index and Treatment)

Column 3 relates to concrete condition index. Column 4 relates to the type and timing of the treatment. Follow the procedures below for the three strategies considered.

1. **Treat at t_p (Example in Figure 13.2):** Find the concrete condition index at present (Chapter 5). Fill out the first row of Column 3 with the condition index at present before treatment (S_p = 15), and the condition index at present after treatment (8.2). Fill out the first row of Column 4 with the type of treatment considered (patch-LSDC, low-slump dense concrete overlay).

   Find the effective service life of the treated concrete (ESL, Chapter 12) (15 years). Find the year to the next cycle of treatment by adding one to the

Figure 13.1. Worksheet for Life-Cycle Cost

Bridge Name & No.:

Year Structure Built:

Bridge Length, ft:

Two-Way ADT & Year:

Component for Treatment:

Component Area, sq ft:

Initially Built with a Protection? (What Type?)

Previously Repaired, Rehabilitated and/or Protected? (When? & What?)

W-C Ratio:

Cover Depth, Avg. & S.D., in.:

Electrical Continuity?

Year Tested:

Spalls, %:

Delams, %:

Bar-Level CL > Threshold, %:

Surface CL, Avg, & S.D., (lb/cy):

Figure 13.1. Worksheet for Life-Cycle Cost (Continued)

(1) Date	(2) Year	(3) Cond. Index (S)	(4) Treatment Type	(5) Agency Cost Initial $	(6) Agency Cost Maint. $	(7) User Cost Prior to Treat. $	(8) User Cost During Treat. $	(9) Discount Factor	(10) Present Worth $

Total Present Worth

Salvage Value

Life-Cycle Cost

Figure 13.2. Example of Tabulated Treatment Strategy (Treat at t_p)

(1) Date	(2) Year	(3) Cond. Index (S)	(4) Treatment Type	(5) Agency Cost Initial $	(6) Agency Cost Maint. $	(7) User Cost Prior to Treat. $	(8) User Cost During Treat. $	(9) Discount Factor	(10) Present Worth $
1992	1	15 8.2	Patch- LSDC	101,955			26,666	1	128,621
1993	2	10.0						0.961	
1994	3	11.8						0.925	
1995	4	13.6						0.888	
1996	5	15.4						0.854	
1997	6	17.2						0.821	
1998	7	19.0						0.790	
1999	8	20.8				1,274		0.759	966
2000	9	22.6				1,775		0.730	1,295
2001	10	24.4				2,413		0.702	1,693
2002	11	26.2				3,207		0.675	2,164
2003	12	28.0				4,184		0.649	2,715
2004	13	29.8				5,368		0.624	3,349
2005	14	31.6				6,788		0.600	4,072
2006	15	33.4				8,472		0.577	4,888
2007	16	35 11.8	Patch- LSDC	214,033			46,666	0.555	144,687
2008	17	13.3						0.534	
2009	18	14.8						0.513	
2010	19	16.3						0.493	
2011	20	17.8						0.474	

Total Present Worth	294,450
Salvage Value	82,380
Life-Cycle Cost	212,070

Figure 13.3. Example of Tabulated Treatment Strategy (Treat at t_m)

(1) Date	(2) Year	(3) Cond. Index (S)	(4) Treatment Type	(5) Agency Cost Initial $	(6) Agency Cost Maint. $	(7) User Cost Prior to Treat. $	(8) User Cost During Treat. $	(9) Discount Factor	(10) Present Worth $
1992	1	15						1	
1993	2	18						0.961	
1994	3	21				1,324		0.925	1,224
1995	4	24				2,259		0.888	2,005
1996	5	27				3,619		0.854	3,090
1997	6	30				5,516		0.821	4,528
1998	7	33				8,076		0.790	6,380
1999	8	35 11.8	Patch- LSDC	214,033			46,666	0.759	197,870
2000	9	14.1						0.730	
2001	10	16.4						0.702	
2002	11	18.7						0.675	
2003	12	21.0				1,323		0.649	858
2004	13	23.3				2,006		0.624	1,251
2005	14	25.6				2,923		0.600	1,753
2006	15	27.9				4,125		0.577	2,380
2007	16	30.2				5,662		0.555	3,142
2008	17	32.5				7,595		0.534	4,055
2009	18	35 11.8	Patch- LSDC	214,033			46,666	0.513	133,738
2010	19	14.1						0.493	
2011	20	16.4						0.474	

Total Present Worth	362,274
Salvage Value	86,499
Life-Cycle Cost	275,774

Figure 13.4 Example of Tabulated Treatment Strategy (Treat between t_p and t_m)

(1) Date	(2) Year	(3) Cond. Index (S)	(4) Treatment Type	(5) Agency Cost Initial $	(6) Agency Cost Maint. $	(7) User Cost Prior to Treat. $	(8) User Cost During Treat. $	(9) Discount Factor	(10) Present Worth $
1992	1	15						1	
1993	2	18						0.961	
1994	3	21				1,324		0.925	1,218
1995	4	24 11.8	Patch-LSDC	139,230			33,333	0.888	153,253
1996	5	13.7						0.854	
1997	6	15.6						0.821	
1998	7	17.5						0.790	
1999	8	19.4						0.759	
2000	9	21.3				1,401		0.730	1,022
2001	10	23.2				1,972		0.702	1,384
2002	11	25.1				2,702		0.675	1,823
2003	12	27.0				3,617		0.649	2,347
2004	13	28.9				4,748		0.625	2,967
2005	14	30.8				6,126		0.600	3,675
2006	15	32.7				7,783		0.577	4,490
2007	16	35 11.8	Patch-LSDC	214,033			46,666	0.555	144,687
2008	17	13.7						0.534	
2009	18	15.6						0.513	
2010	19	17.5						0.493	
2011	20	19.4						0.474	

Total Present Worth	316,866
Salvage Value	72,083
Life-Cycle Cost	244,782

effective service life of the treated concrete (1 + 15 = Year 16). Fill out those boxes in Columns 3 and 4 which correspond to the year of next cycle of treatment (Year 16) with the maximum tolerable condition index (S_m = 35), the condition index after treatment (11.8; use Chapter 11 to decompose S_m and Chapter 5 to determine the index just after treatment), and the type of treatment in the next cycle of treatment (patch LSDC).

Find the approximate concrete condition index for each consecutive year after the treatment from Equation 13.1. Fill out the appropriate boxes of Column 3 with the approximate condition indices determined (10.0 through 33.4).

$S_{\text{After Treatment}}$ = [(S_m - Index just after Treatment) x (No. of Years after Treatment) / (Effective Service Life after Treatment)] + [Index just after Treatment] (Equation 13.1)

[Equation 13.1 assumes a linear relation between condition index and time. This approximation is justified, since usually after the treatment the slope of the "S" curve applies. However, if the exact value of condition index is required, Equations 6.1, 6.3, and 6.4 may be used.]

Do not repeat treating the concrete, if the effective service life of the treated concrete (in this example 15 years) is more than the remaining years in the consideration period (in this example 5 years).

2. **Treat at t_m (Example in Figure 13.3):** Find concrete condition index for each consecutive year starting with the present year, t_p, and ending with t_m (Chapter 6). Fill out the appropriate boxes of Column 3 with the condition indices determined (S_p = 15 through S_m = 35). Also, fill out the box for S_m with the index just after the treatment (11.8; use Chapter 11 to decompose S_m and Chapter 5 to determine the index just after treatment). Fill out the box in Column 4 that corresponds to S_m with the type of treatment (patch-LSDC).

   Find the effective service life of the treated concrete (ESL, Chapter 12) (10 years). Find the year to the next cycle of treatment by adding the effective service life of the treated concrete to the year of treatment (10 + 8 = Year 18). Fill out those boxes in Columns 3 and 4 which correspond to the year of next cycle of treatment (Year 18) with the maximum tolerable condition index (S_m = 35), the condition index after treatment (11.8), and the type of treatment in the next cycle (patch-LSDC).

   Find the approximate concrete condition index for each consecutive year after the treatment from Equation 13.1. Fill out the appropriate boxes of Column 3 with the approximate condition indices determined (14.1 through 32.5).

$S_{After\ Treatment}$ = [(S_m - Index just after Treatment) x (No. of Years after Treatment) / (Effective Service Life after Treatment)] + [Index just after Treatment] (Equation 13.1)

Do not repeat treating the concrete if the effective service life of the treated concrete (in this example 10 years) is more than the remaining years in the consideration period (in this example 3 years).

3. **Treat between t_p and t_m (Example in Figure 13.4):** Find the concrete condition index for each consecutive year starting with the present year, t_p, and ending with (t_p + t_m) / 2 (Chapter 6). Fill out the appropriate boxes of Column 3 with the condition indices determined (S_p = 15 through S_{p-m} = 24). Also, fill out the box for S_{p-m} with the index just after the treatment (11.8; use Chapter 11 to decompose S_{p-m} and Chapter 5 to determine the index just after treatment). Fill out the box in Column 4 that corresponds to S_{p-m} with the type of treatment (patch-LSDC).

   Find the effective service life of the treated concrete (12 years; use Chapter 12 to determine the ESL). Find the year to the next cycle of treatment by adding the effective service life of the treated concrete to the year of treatment (12 + 4 = Year 16). Fill out those boxes in Columns 3 and 4 which correspond to the year of next cycle of treatment (Year 16) with the maximum tolerable condition index (S_m = 35), the condition index after treatment (11.8), and the type of treatment in the next cycle (e.g., patch-LSDC).

   Find the approximate concrete condition index for each consecutive year after the treatment from Equation 13.1. Fill out the appropriate boxes of Column 3 with the approximate condition indices determined (13.7 through 32.7).

   $S_{After\ Treatment}$ = [(S_m - Index just after Treatment) x (No. of Years after Treatment) / (Effective Service Life after Treatment)] + [Index just after Treatment] (Equation 13.1)

   Do not repeat treating the concrete if the effective service life of the treated concrete (in this example, 12 years) is more than the remaining years in the consideration period (in this example, 5 years)

Step 3 (Agency Costs)

Columns 5 and 6 relate to agency costs. Fill out the appropriate boxes of Column 5 with the cost associated with the application of the treatment (Chapter 9).

Fill out the appropriate boxes of Column 6 with the annual cost of monitoring/maintaining the treatment (Chapter 9). For example, in Figures 13.2, 13.3 and 13.4 there were no agency maintenance costs.

Step 4 (User Costs Prior to Treatment)

Column 7 is for user costs prior to the treatment. Using the condition index given in Column 3, estimate the user costs prior to the treatment for each consecutive year in the planning horizon (Chapter 10).

Step 5 (User Costs During Treatment)

Column 8 is for user costs during the treatment (Chapter 10).

Step 6 (Discount Factor)

Column 9 is for the discount factor. Using the equation given below, find the discount factor for each consecutive year in the planning horizon; alternatively, use Figure 13.5.

$$DF = 1 / (1 + EI)^{n-1} \qquad \text{(Equation 13.2)}$$

where

DF = discount factor

EI = effective interest rate = interest rate minus inflation rate

n = number of each consecutive year in the planning horizon

Fill out the boxes of Column 9 with the discount factors.

Step 7 (Present Worth)

Column 10 gives the sum of the costs in each consecutive year in "current dollars" (present worth). Multiply the sum of all costs in each consecutive year by the corresponding discount factor, and fill out the boxes of Column 10 with the products.

Figure 13.5. Discount Factors

Consecutive years	EI[1] = 1%	EI = 2%	EI = 3%	EI = 4%	EI = 5%
1	1.000	1.000	1.000	1.000	1.000
2	0.990	0.980	0.971	0.962	0.952
3	0.980	0.961	0.943	0.925	0.907
4	0.971	0.942	0.915	0.889	0.864
5	0.961	0.924	0.888	0.855	0.823
6	0.951	0.906	0.863	0.822	0.784
7	0.942	0.888	0.837	0.790	0.746
8	0.933	0.871	0.813	0.760	0.711
9	0.923	0.853	0.789	0.731	0.677
10	0.914	0.837	0.766	0.703	0.645
11	0.905	0.820	0.744	0.676	0.614
12	0.896	0.804	0.722	0.650	0.585
13	0.887	0.788	0.701	0.625	0.557
14	0.879	0.773	0.681	0.601	0.530
15	0.870	0.758	0.661	0.577	0.505
16	0.861	0.743	0.642	0.555	0.481
17	0.853	0.728	0.623	0.534	0.458
18	0.844	0.714	0.605	0.513	0.436
19	0.836	0.700	0.587	0.494	0.416
20	0.828	0.686	0.570	0.475	0.396

1: EI = Effective Interest Rate = Interest rate - Inflation rate

Step 8 (Total Present Worth)

Add up all costs in Column 10. This is the total present worth, as shown in the bottom of Figure 13.1.

Step 9 (Salvage Value)

Use the procedure described below to determine the discounted salvage value of the last treatment in the last year of the planning horizon (i.e., the 20th year), as shown in the bottom of Figure 13.1. Salvage value applies to the remaining useful life of the treatment beyond the planning horizon, and is determined from the following equation.

$$SLVG = (COST)\ (RS/ESL)\ (DF_{20}) \qquad \text{(Equation 13.3)}$$

where

SLVG = salvage value, present worth, dollars

COST = cost of last treatment (sum of all costs in the year of last treatment before discounting), dollars

RS = remaining effective service life of the concrete component after treatment (last treatment) beyond the planning horizon, years

ESL = estimated effective service life of treated concrete, years

DF_{20} = discount factor corresponding to the last year in the planning horizon (i.e., 20th year)

Step 10 (Life-Cycle Cost)

Subtract the discounted salvage value (Step 9) from the total present worth (Step 8) to find the life-cycle cost for the strategy considered. Fill out the "Life-Cycle Cost" box in the bottom of Figure 13.1.

Step 11 (Life-Cycle Cost Comparison)

Compare the life-cycle costs of the three strategies (i.e., treat at t_p, treat at t_m, and treat between t_p and t_m), and select the strategy with the minimum life-cycle cost.

14. Worked Example

The example in this chapter illustrates how the methodology introduced in this handbook is applied to make a decision to treat a concrete bridge component.

[To convert to metric units in this example: one square foot is 0.929 square meters; one inch is 2.54 centimeters; one pound per cubic yard is 0.59 kilograms per cubic meter; one dollar per square foot is 10.76 dollars per square meter; and one foot is 0.3 meters.]

14.1 General Description of the Example

The concrete bridge component to be examined is a bridge deck with an area of 10,000 square feet. The concrete bridge deck was placed in 1978, and it contains "black" reinforcing steel. The concrete is a conventional concrete with a specified water-cement ratio of 0.45 (assume actual water-cement ratio = 0.45 + $\underline{0.03}$ = 0.48, unless field information exists) and a specified bar cover depth of 1.5 inches. The concrete has not received any treatment since 1978.

The average two-way daily traffic volume across the bridge is 15,000 vehicles. The concrete deck has been exposed to de-icing salt during its service, but background chlorides do not exist in the concrete. Reinforcing steel corrosion-induced deterioration has been present and is a concern. The expected remaining service life of the structure due to bridge functional features is 50 years (i.e., unlimited remaining service life, see Chapter 3).

The highway agency that owns the bridge would like to determine when the bridge should be treated against chloride-induced corrosion and what type of treatment should be applied.

14.2 Systematic Procedure to Determine Type and Timing of Treatment

A: Test Concrete (Chapter 4)

The concrete deck was tested in 1992 (present year) and the following results were obtained.

Visual Inspection:

- Spalls (1 percent of deck area)
- Patches (none)
- Scaling (none)
- Pop-outs (none)
- Cracks (minor, no active cracks)
- Wheeltrack wear (not significant)

Delamination Survey

- Delamination (5 percent of the deck area)

Cover Depth

- Average bar cover depth (1.40 inches)
- Standard deviation (0.50 inches)

Reinforcing Steel Electrical Continuity

- O.K.

Chloride Profiles

- Average chlorides at top bars (0.0875 percent of concrete weight, or 3.5 pounds per cubic yard)

- Percent of concrete samples at top bars with chlorides higher than the threshold of 0.035 percent of concrete weight, or 1.4 pounds per cubic yard (40 percent)

- average surface chlorides (0.250 percent of concrete weight, or 10 pounds per cubic yard)

  standard deviation (0.05 percent of concrete weight, or 2 pounds per cubic yard)

Corrosion Potential Survey

- Not conducted

Rate of Corrosion Measurements

- Not conducted

Permeability/Resistivity Test

- Not conducted

Overall Evaluation: Non-corrosion related deterioration is not significant. Thus, continue using this manual.

B: Condition Determination (Chapter 5)

Use Equation 5.2, or Figure 5.1, to determine the concrete condition index.

$S = [CL + 2.5(DELAM) + 7.5(SPALL)] / 8.5$

$S = [40 + 2.5(5) + 7.5(1)] / 8.5$

$S = 7.1$

C: Prediction of Performance (Chapter 6)

Use Section 6.2, "Concrete not Repaired, Rehabilitated and/or Protected Previously and without a Special Protection."

Step 1

$t_p = 1992 - 1978 = 14$ years

$S_p = 7.1$

Since S_p more than 1.9, use Steps 2 and 3 in Section 6.2.

Step 2

Use Equation 6.2, or Figure 6.1, to find t_d (concrete age at first sign of deterioration).

$$t_d = [(2.695\ d^{1.22}\ t^{0.21}) / (Z_t^{0.42}\ P)]^{0.3265}$$

$$t_d = \{[2.695\ (1.4 - 1.282 \times 0.50)^{1.22} \times 14^{0.21}] / [(0.250 + 1.282 \times 0.05)^{0.42} \times 0.48\}^{0.8265}$$

t_d = 7.5 years, and

S_d = 1.9

Step 3

Use Equations 6.4 and 6.5 to find Parameters B and A. Alternatively, use Figures 6.3 and 6.4.

$$B = \ln\{[S_d(100 - S_p)] / [S_p(100 - S_d)]\} / (t_d - t_p)$$

$$B = \ln\{[1.9(100 - 7.1)] / [7.1(100 - 1.9)]\} / (7.5 - 14)$$

$$B = 0.21$$

$$A = [(100 - S_p) / (S_p] / [\exp(-Bt_p)]$$

$$A = [(100 - 7.1) / 7.1] / [\exp(-0.21 \times 14)]$$

$$A = 245.3$$

Thus, the concrete performance equation is:

$$S_t = 100 / [\ 1 + 245.3\ \exp(-0.21\ t)]$$

D: Evaluation of Performance (Chapter 7)

Treatment Consideration Period = $t_m - t_p$

Find t_m from Equation 7.2, or Figure 7.1, assuming S_m = 35.

$$t_m = -\{\ln[(100 - S_m) / (A\ S_m)]\} / B$$

$$t_m = -\{\ln[(100 - 35) / (245.3 \times 35)]\} / 0.21$$

t_m = 23.3 years, and

t_p = 14 years

Treatment Consideration Period = 23.3 - 14 = 9.3 years (i.e., 1992 to 2001)

Use the rest of the handbook to determine the timing of the treatment within the treatment consideration period, for a compatible treatment.

E: Compatible Treatment Alternatives (Chapter 8)

Use Table 8.1 to screen out the incompatible treatment alternatives. The rest of this example will only consider one alternative (patching and low-slump dense concrete overlay) in order to determine its optimum timing for maximum cost-effectiveness. The same procedure can be used to determine the timing and life-cycle costs of each compatible alternative for comparison.

F: Cost Items Associated with Treatment, Agency Costs (Chapter 9)

- Removing/patching deteriorated concrete ($35 per square foot of deteriorated concrete)
- Scarifying deck ($0.75 per square foot of deck)
- Placing and curing 1.5 in. LSDC overlay ($2.85 per square foot of deck)
- Traffic control ($2.00 per square foot of deck area)

G: Cost Items Associated with Treatment, User Costs (Chapter 10)

Prior-to-Treatment Costs

Use Equation 10.2, or Figure 10.3.

$$U_2 = K_2 [S / S_m]^4 [365\ q_o]$$

where

U_2 = user costs, dollars per year
S_m = 35
q_o = 15,000 vehicles per day
K_2 = a t_f K_1

Assume

t_f = 0.06 minutes (free flow travel time across 300 ft bridge),

K_1 = \$0.1666 per minute per vehicle, and
a = 50% (50 percent reduction in travel time).

This will give

K_2 = 0.50 x 0.06 x 0.1666 = \$0.005 per vehicle.

then

$U_2 = (0.005)\ [S/35]^4\ [365 \times 15{,}000]$
$U_2 = 27{,}375\ [S/35]^4$

Use the relation above, or Figure 10.3, to find U_2 for a given S when tabulating a strategy in I, below.

During-Treatment Costs

Use Equation 10.2, or Figure 10.1.

$$U_1 = K_1\ t_t\ t_c\ q_o$$

where

U_1 = user costs, dollars
K_1 = \$0.1666 per minute per vehicle
t_c = duration of repair, days
q_o = 15,000 vehicles per day
t_t = 2 minutes (assume detour around the bridge)

then

$U_1 = (0.1666)(2)(t_c)(15{,}000)$
$U_1 = 4999.5\ t_c$

Use the relation above, or Figure 10.1, to find U_1 for a given t_c when tabulating a strategy in Part I, below.

H: Prediction of Performance, Treated Concrete (Chapter 12)

Use Case 1, "Concrete not Repaired, Rehabilitated and/or Protected Previously." Condition 4, in which the rate of corrosion decreases gradually after the treatment, applies to this example. Use Equation 12.4, or Figure 12.6, to predict the effective service life (ESL) after the treatment (i.e., years to condition index of S_m = 35 after the treatment).

$$ESL = \{[(t^* - t_o)^2 + K(t_m - t_o)^2]^{0.5} - (t^* - t_o)\} / K$$

Assume K = -1/5 (ratio of slope of rate of corrosion line after treatment to slope of rate of corrosion line before treatment). Since t_d = 7.5 years (Part C), t_o = 5 years (Figure 12.3), and t_m = 23.3 years (Part D), then:

$$ESL = \{[(t^* - 5)^2 + (-1/5)(23.3 - 5)^2]^{0.5} - (t^* - 5)\} / (-1/5)$$
$$ESL = 5\{(t^* - 5) - [(t^* - 5)^2 - 70]^{0.5}\}$$

Use the relation above to find ESL for a given t^* when tabulating a strategy in I, below.

I: Optimum Treatment and Time of Treatment (Chapter 13)

Consider treating the deck with patch-LSDC (patching and low-slump dense concrete overlay; contaminated concrete left in place) at three different points in time (three strategies) as shown below.

- Concrete age = t_p (age 14 years, year 1992)
- Concrete age = t_m (age 23.3 years, year 2001)
- Concrete age = $(t_p + t_m)/2$ (age 18.65 years, year 1997)

Use Section 13.1 and the worksheet in Figure 13.1, to estimate the life-cycle cost of each strategy. (Results are shown in Figures 14.1, 14.2, and 14.3 at the end of this chapter.)

Step 1, Planning Horizon (All Strategies)

From Chapter 3, since the remaining service life of the bridge is 50 years (higher than 30 years), the planning horizon is 20 years. Fill out Column 1 in Figure 13.1 by starting with the year 1992 and ending with the year 2011. Fill out Column 2 by starting with Year 1 and ending with Year 20.

Step 2, Condition Index and Treatment

Strategy, Treat at t_p

Fill out the first row of Column 3 with the condition index at present before treatment (S = 7.1) and after treatment (S = 4.7). Fill out the first row of Column 4 with the type of treatment considered (patch-LSDC).

From Part H, the effective service life of concrete after treatment, ESL, is

$$ESL = 5\ \{(t^* - 5) - [(t^* - 5)^2 - 70]^{0.5}\}$$

where $t^* = t_p = 14$ years

$$ESL = 5\ \{(14 - 5) - [(14 - 5)^2 - 70]^{0.5}\}$$
$$ESL = 28 \text{ years}$$

Find the year to the next cycle of treatment by adding one to the effective service life of the concrete after treatment (1 + 28 = Year 29). Therefore, no further treatment is required during the planning horizon.

Find the approximate concrete condition index for each consecutive year after the treatment from Equation 13.1.

$S_{\text{After Treatment}}$ = [(S_m - Index just after Treatment) x (No. of Years after Treatment)/ (Effective Service Life after Treatment)] + [Index just after treatment]

$S_{\text{After Treatment}}$ = [(35 - 4.7) x (No. of Years after Treatment) / (28)] + [4.7]

$S_{\text{After Treatment}}$ = (1.08) x (No. of Years after Treatment) + 4.7

No. of Years After Treatment	S After Treatment	Year in Planning Horizon
1	5.8	2
2	6.9	3
3	7.9	4
4	9.0	5
5	10.1	6
6	11.2	7
7	12.3	8
8	13.3	9
9	14.4	10
10	15.5	11
11	16.6	12
12	17.7	13
13	18.7	14
14	19.8	15
15	20.9	16
16	22.0	17
17	23.1	18
18	24.1	19
19	25.2	20

Strategy, Treat at t_m

Use Equation 6.1, or Figure 7.1, to predict the concrete condition index prior to treatment.

$$S_t = 100 / [1 + A \exp(-Bt)]$$

Concrete Age, t	S Before Treatment	Year in Planning Horizon
14	7.1	1
15	8.6	2
16	10.4	3
17	12.6	4
18	15.0	5
19	17.9	6
20	21.2	7
21	24.9	8
22	29.0	9
23	33.5	10
24	38.3 > S_m = 35	11

Fill out the appropriate boxes of Column 3 with the condition indices of S = 7.1 through S = 33.5. Also, fill out the box for S = 33.5 with the index just after treatment (i.e., 11.8). Fill out the box in Column 4 that corresponds to S = 33.5 with the type of treatment, patch-LSDC.

From Part H, the effective service life of concrete after treatment, ESL, is:

$$ESL = 5 \{(t^* - 5) - [(t^* - 5)^2 - 70]^{0.5}\}$$

where $t^* = t_m = 23.3$ years

$$ESL = 5 \{(23.3 - 5) - [(23.3 - 5)^2 - 70]^{0.5}\}$$

$$ESL = 10 \text{ years}$$

The year to the next cycle of treatment is 10 + 10 = Year 20. Fill out those boxes in Columns 3 and 4, which correspond to Year 20 with S_m = 35 and the type of treatment (patch-LSDC), respectively.

Find the approximate concrete condition index for each consecutive year after the treatment using Equation 13.1.

$S_{\text{After Treatment}}$ = [(S_m - Index just after Treatment) x (No. of Years after Treatment)/ (Effective Service Life after Treatment)] + [Index Just after Treatment]

$S_{After\ Treatment}$ = [(35 - 11.8) x (No. of Years after Treatment) / (10)] + [11.8]

$S_{After\ Treatment}$ = (2.32) x (No. of Years after Treatment) + 11.8

No. of Years After Treatment	S After Treatment	Year in Planning Horizon
1	14.1	11
2	16.4	12
3	18.7	13
4	21.0	14
5	23.3	15
6	25.6	16
7	27.9	17
8	30.2	18
9	32.5	19
10	35	20

Strategy, Treat between t_p and t_m

Use Equation 6.1, or Figure 7.1, to predict the concrete condition index prior to treatment.

$S_t = 100 / [1 + A \exp(-Bt)]$

Concrete Age, t	S Before Treatment	Year in Planning Horizon
14	7.1	1
15	8.6	2
16	10.4	3
17	12.6	4
18	15.0	5
19	17.9	6

Fill out the appropriate boxes of Column 3 with the condition indices of S = 7.1 through S = 17.9. Also, fill out the box for S = 17.9 with the index just after treatment (i.e., 10.3). Fill out the box in Column 4 that corresponds to S = 17.9 with the type of treatment, patch-LSDC.

From Part H, the effective service life of concrete after treatment, ESL, is

$ESL = 5 \{(t^* - 5) - [(t^* - 5)^2 - 70]^{0.5}\}$

where

$t^* = (t_p + t_m)/2 = 18.65$ years

$ESL = 5\ (18.65 - 5) - [(18.65 - 5)^2 - 70]^{0.5}\}$

ESL = 14 years

The year to the next cycle of treatment is 14 + 6 = Year 20. Fill out those boxes in Columns 3 and 4 which correspond to Year 20 with S_m = 35 and the type of treatment, patch-LSDC.

Find the approximate concrete condition index after treatment using Equation 13.1.

$S_{After\ Treatment}$ = [(S_m - Index just after Treatment) x (No. of Years after Treatment)/ (Effective Service Life after Treatment)] + [Index just after Treatment]

$S_{After\ Treatment}$ = [(35 - 10.3) x (No. of Years after Treatment) / (14)] + [10.3]

$S_{After\ Treatment}$ = (1.8) x (No. of Years after Treatment) + 10.3

No. of Years After Treatment	S After Treatment	Year in Planning Horizon
1	12.1	7
2	13.9	8
3	15.7	9
4	17.5	10
5	19.3	11
6	21.1	12
7	22.9	13
8	24.7	14
9	26.5	15
10	28.3	16
11	30.1	17
12	31.9	18
13	33.7	19
14	35	20

Step 3, Agency Costs

Fill out the appropriate boxes of Column 5 in Figure 13.1 with the cost associated with the application of the treatment (see F above, for itemized costs).

Strategy, Treat at t_p

DELAM = 5%

SPALL = 1%

Total Area Deteriorated = 5 + 1 = 6%

1. Removing and patching concrete: (6 percent of 10,000 square feet at $35 per square foot) = $21,000
2. Concrete overlay (10,000 square feet at $5.60 per square foot, the total costs for scarifying the deck, placing and curing the overlay, and providing traffic control) = $56,000

Total Agency Cost = 21,000 + 56,000 = $77,000

Strategy, Treat at t_m

Use Equations 11.1 through 11.3 to decompose the condition index of S = 33.5.

CL = 5 S
CL = 5 (33.5) = 167.5 > 100, then, CL = 100%

DELAM = (8.5 S - CL) / (2.5 + 7.5/N)
DELAM = (8.5 x 33.5 - 100) / (2.5 + 7.5/4) = 42.2%

SPALL = DELAM / N
SPALL = 42.2 / 4 = 10.5%

Total Area Deteriorated = 42.5 + 10.5 = 53%

1. Removing and patching concrete (53 percent of 10,000 square foot at $35 per square foot) = $185,500
2. Concrete overlay (10,000 square feet at $5.60 per square foot) = $56,000

Total Agency Cost = 185,500 + 56,000 = $241,500

Use the same agency cost when treatment is repeated at S_m, with sufficient accuracy.

Strategy, Treat between t_p and t_m

Use Equations 11.1 through 11.3 to decompose the condition index of S = 17.9.

CL = 5 S
CL = 5 (17.9) = 89.5%

DELAM = (8.5 S - CL) / (2.5 + 7.5/N)

DELAM = (8.5 x 17.9 - 89.5) / (2.5 + 7.5/4) = 14.3%

SPALL = DELAM / N
SPALL = 14.3 / 4 = 3.6%

Total Area Deteriorated = 14.3 + 3.6 = 17.9%

1. Removing and patching concrete (17.9 percent of 10,000 square feet at $35 per square foot) = $62,650
2. Concrete overlay: (10,000 square feet at $5.60 per square foot) = $56,000

Total Agency Cost = 62,650 + 56,000 = $118,650

Use $241,500 as agency cost when treatment is repeated at S_m, with sufficient accuracy (see previous strategy).

Step 4, User Cost "Prior to Treatment"

To find user costs prior to treatment (see part G above for U_2):

Strategy, Treat at t_p

Year in Plan. Horizon	S	U_2
1	7.44-4.7	< $1,000
2	5.8	< $1,000
3	6.9	< $1,000
4	7.9	< $1,000
5	9.0	< $1,000
6	10.1	< $1,000
7	11.2	< $1,000
8	12.3	< $1,000
9	13.3	< $1,000
10	14.4	< $1,000
11	15.5	$1,052
12	16.6	$1,385
13	17.7	$1,790
14	18.7	$2,230
15	19.8	$2,803
16	20.9	$3,480
17	22.0	$4,273
18	23.1	$5,194
19	24.1	$6,153
20	25.2	$7,356

Fill out the boxes of Column 7 with the user costs.

Strategy, Treat at t_m

Year in Plan. Horizon	S	U_2
1	7.1	< $1,000
2	8.6	< $1,000
3	10.4	< $1,000
4	12.6	< $1,000
5	15.0	< $1,000
6	17.9	$1,872
7	21.2	$3,684
8	24.9	$7,012
9	29.0	$12,902
10	33.5-11.8	< $1,000
11	14.1	< $1,000
12	16.4	$1,319
13	18.7	$2,230
14	21.0	$3,547
15	23.3	$5,376
16	25.6	$7,835
17	27.9	$11,053
18	30.2	$15,174
19	32.5	$20,352
20	35.0-11.8	< $1,000

Fill out the boxes of Column 7 with the user costs.

Strategy, Treat between t_p and t_m

Year in Plan. Horizon	S	U_2
1	7.1	<$1,000
2	8.6	< $1,000
3	10.4	< $1,000
4	12.6	< $1,000
5	15.0	< $1,000
6	17.9-10.3	<$1,000
7	12.1	< $1,000
8	13.9	< $1,000
9	15.7	$1,108

Year in Plan. Horizon	S	U_2
10	17.5	$1,710
11	19.3	$2,531
12	21.1	$3,615
13	22.9	$5,016
14	24.7	$6,789
15	26.5	$8,996
16	28.3	$11,701
17	30.1	$14,974
18	31.9	$18,890
19	33.7	$23,528
20	35.0-11.8	<$1,000

Fill out the boxes of Column 7 with the user costs.

Step 5, User Cost "During Treatment"

Fill out the appropriate boxes of Column 8 with the user costs during the treatment (See G above for U_1).

Strategy, Treat at t_p

To find user costs during the treatment

Concrete Removal/Patching at 200 square feet per day =	3 days
Overlay Placing/Curing at 2,000 square feet per day =	5 days
Total time (t_c) =	8 days
U_1 =	$40,000

Strategy, Treat at t_m

To find user costs during the treatment

Concrete Removal/Patching at 200 square feet per day =	27 days
Overlay Placing/Curing at 2,000 square feet per day =	5 days
Total time (t_c) =	32 days
U_1 =	$160,000

Use the same user cost when treatment is repeated at S_m.

Strategy, Treat between t_p and t_m

To find user costs during the treatment

Concrete Removal/Patching at 200 square feet per day =	9 days
Overlay Placing/Curing at 2,000 square feet per day =	5 days
Total time (t_c) =	14 days
U_1 =	\$70,000

Use \$160,000 as user cost during treatment when treatment is repeated at S_m.

Step 6, Discount Factor (All Strategies)

Find the discount factor for each consecutive year in the consideration period, assuming an interest rate of 7 percent and an inflation rate of 3 percent, or an effective interest rate of 7 - 3 = 4 percent (Equation 13.2, or Figure 13.5). Fill out the boxes in Column 9 with the discount factors.

Step 7, Present Worth (All Strategies)

Multiply the sum of all costs in each consecutive year by the corresponding discount factor, and fill out the boxes of Column 10 with the products.

Step 8, Total Present Worth (All Strategies)

Add up all the costs in Column 10 to find the total present worth of each strategy.

Step 9, Salvage Value

Find discounted salvage value of the last treatment and fill out the corresponding box in the bottom of Figure 13.1 (Equation 13.3).

Strategy, Treat at t_p

$$SLVG = (COST)\ (RS/ESL)\ (DF_{20})$$

$$SLVG = (\$77,000 + \$40,000)\ [(28 - 20)/28]\ (0.474)$$
$$SLVG = \$15,845$$

Strategy, Treat at t_m

SLVG = ($241,500 + $160,000) [(10 - 1)/10] (0.474)
SLVG = $171,059

Strategy, Treat between t_p and t_m

SLVG = ($241,500 + $160,000) [(14 - 1)/14] (0.474)
SLVG = $176,716

Step 10, Life-Cycle Cost

Subtract the discounted salvage value (Step 9) from the total present worth (Step 8) to find the life-cycle cost for each strategy. Fill out the "Life-Cycle Cost" box in the bottom of Figure 13.1.

Strategy, Treat at t_p

Life-Cycle Cost = $136,074 - $15,845 = $120,229

Strategy, Treat at t_m

Life-Cycle Cost = $526,961 - $171,066 = $355,895

Strategy, Treat between t_p and t_m

Life-Cycle Cost = $399,431 - $176,716 = $222,715

Step 11, Life-Cycle Cost Comparison

If the deck is treated at the present (year 1992), the life-cycle cost will be 54 percent of the life-cycle cost if it were treated in 1997, and it will be 34 percent of the life-cycle cost if it were treated in 2001.

Treatment Time	Life Cost, dollars
1992	120,229
1997	222,715
2001	355,895

Figure 14.1. Worked Example of Tabulated Treatment Strategy (Treat at t_p)

Date	Year	Cond. Index (S)	Treatment Type	Agency Cost Initial $	Agency Cost Maint. $	User Cost Prior to Treat. $	User Cost During Treat. $	Discount Factor	Present Worth $
1992	1	7.1 4.7	Patch- LSDC	77,000			40,000	1	117,000
1993	2	5.8						0.961	
1994	3	6.9						0.925	
1995	4	7.9						0.888	
1996	5	9.0						0.854	
1997	6	10.1						0.821	
1998	7	11.2						0.790	
1999	8	12.3						0.759	
2000	9	13.3						0.730	
2001	10	14.4						0.702	
2002	11	15.5				1,052		0.675	710
2003	12	16.6				1,385		0.649	898
2004	13	17.7				1,790		0.624	1,116
2005	14	18.7				2,230		0.600	1,338
2006	15	19.8				3,803		0.577	1,617
2007	16	20.9				3,480		0.555	1,931
2008	17	22.0				4,273		0.534	2,281
2009	18	23.1				5,194		0.513	2,664
2010	19	24.1				6,153		0.493	3,033
2011	20	25.2				7,356		0.474	3,486

Total Present Worth	136,074
Salvage Value	15,845
Life-Cycle Cost	120,229

Figure 14.2. Worked Example of Tabulated Treatment Strategy (Treat at t_m)

Date	Year	Cond. Index (S)	Treatment Type	Agency Cost Initial $	Agency Cost Maint. $	User Cost Prior to Treat. $	User Cost During Treat. $	Discount Factor	Present Worth $
1992	1	7.1						1	
1993	2	8.6						0.961	
1994	3	10.4						0.925	
1995	4	12.6						0.888	
1996	5	15.0						0.854	
1997	6	17.9				1,872		0.821	1,536
1998	7	21.2				3,684		0.790	2,910
1999	8	24.9				7,012		0.759	5,332
2000	9	29.0				12,982		0.730	9,476
2001	10	33.5 11.8	Patch-LSDC	241,500			160,000	0.702	281,853
2002	11	14.1						0.675	
2003	12	16.4				1,319		0.649	856
2004	13	18.7				2,230		0.624	1,391
2005	14	21.0				3,547		0.600	2,128
2006	15	23.3				5,376		0.577	3,101
2007	16	25.6				7,835		0.555	4,348
2008	17	27.9				11,053		0.534	5,902
2009	18	30.2				15,174		0.513	7,784
2010	19	32.5				20,352		0.493	10,033
2011	20	35 11.8	Patch-LSDC	241,500			160,000	0.474	190,311

Total Present Worth	526,961
Salvage Value	171,066
Life-Cycle Cost	355,895

Figure 14.3. Worked Example of Tabulated Treatment Strategy (Treat between t_p and t_m)

Date	Year	Cond. Index (S)	Treatment Type	Agency Cost Initial $	Agency Cost Maint. $	User Cost Prior to Treat. $	User Cost During Treat. $	Discount Factor	Present Worth $
1992	1	7.1						1	
1993	2	8.6						0.961	
1994	3	10.4						0.925	
1995	4	12.6						0.888	
1996	5	15.0						0.854	
1997	6	17.9 10.3	Patch-LSDC	118,650			70,000	0.821	154,881
1998	7	12.1						0.790	
1999	8	13.9						0.759	
2000	9	15.7				1,108		0.730	808
2001	10	17.5				1,710		0.702	1,200
2002	11	19.3				2,531		0.675	1,708
2003	12	21.1				3,615		0.649	2,346
2004	13	22.9				5,016		0.625	3,135
2005	14	24.7				6,789		0.600	4,073
2006	15	26.5				8,996		0.577	5,190
2007	16	28.3				11,701		0.555	6,494
2008	17	30.1				14,974		0.534	7,996
2009	18	31.9				18,890		0.513	9,690
2010	19	33.7				23,528		0.493	11,599
2011	20	35 11.8	Patch-LSDC	241,500			160,000	0.474	190,311

Total Present Worth	399,431
Salvage Value	176,716
Life-Cycle Cost	222,715

PART III — USER MANUAL FOR CORRODE

1. CORRODE Basics

1.1 What is CORRODE?

The CORRODE system was produced as part of this SHRP Project. The objective of this project was to develop a procedure to evaluate different preventive or corrective strategies for mitigating corrosion of reinforced concrete bridge decks. This analysis entails both an accounting of the corrosion mechanism itself and its progression to visible signs of distress, and the evaluation of alternative treatments within a life-cycle cost framework. By applying this procedure, you are able to analyze this problem in the following stages:

- To determine the current state of corrosion of a bridge deck and estimate its future deterioration (rate of increase in distress over time),
- To apply a life-cycle cost analysis to compute the optimal time (i.e., the year in which total life-cycle costs are minimized) for performing a given treatment that you define,
- To compare the optimal times and costs of various preventive and corrective strategies to arrive at the most economical alternative.

This project has embodied this analysis in two ways: a handbook in Part II, and a computer system — CORRODE. These two solutions are based upon the same basic methodology, but they "stand alone," in that you may use one without reference to the other.

This manual accompanies the CORRODE computer system; it is intended to help you understand the various system options available and to provide tips on useful approaches. Chapters 1 and 2 provide an overview of the system's capabilities and instruct you in the basic techniques of navigating through the system, selecting from the options available, and performing different tasks (data input, executing commands, etc.). Chapters 3 through 7 provide additional details about each option or feature to help you understand the implications of each choice. In most cases, once you have mastered the basics, you will find operating the system very easy and intuitive.

You are encouraged to explore the system's features and operating style as soon as you have read Chapters 1 and 2 and scanned the remaining chapters to get a feel for the various capabilities of the system and the scope of its analyses. You may want to develop some example problems and work them through the full range of the system's features. As you do so, please observe how the system handles certain critical tasks and functions: e.g., how it relates data files to different bridges, and its general approach to creating and deleting files. Please consult the manual for special instructions and notes regarding these operations, particularly in the deletion of files.

1.2 Installing CORRODE

CORRODE is easy to install. Please be sure you have the latest version of a CORRODE "Install Disk," and follow these guidelines:

- Enter DOS on your system and change to the directory on your hard drive or network system file server in which you would like to install CORRODE. This may be either a root directory (e.g., C:\, D:\) or a subdirectory (e.g., C:\BRIDGES, D:\BRIDGE\ANALYSIS). The Install Disk will create its own subdirectory, named CORRODE, within the particular directory that you select.

- Insert the Install Disk in the a: or b: drive. Change to that drive by typing a: or b:, as appropriate. When you receive the **A:>** or **B:>** prompt, type **install.**

- You will receive a prompt for the identifying letter of the drive on which CORRODE will be installed (the same letter you selected in the first step). Enter only the letter identifying the drive (e.g., **C, D,** etc.) and press **F10.**

- CORRODE will automatically load into the hard disk directory that you specify. For example, if you change to the hard drive directory D:\BRIDGE\ANALYSIS, and respond with a **"D"** when the installation procedure prompts you for the relevant drive letter, the CORRODE system will be installed in the directory D:\BRIDGE\ANALYSIS\CORRODE.

- CORRODE will inform you when the installation is complete. You may now start the system by typing **corrode** and pressing **Enter.**

1.3 Printer File

CORRODE's installation procedure automatically loads a file SETUP.PRN in the CORRODE subdirectory. This file is used to send formatting instructions (i.e., escape

codes controlling line length, font size, spacing, compression, etc.) to the printer. This file **must** exist in the CORRODE subdirectory, **even if it is an empty file.**

The commands contained in SETUP.PRN are sent to the printer by CORRODE prior to printing any reports. When you quit the system, CORRODE sends the commands stored in file RESET.PRN to the printer to restore its settings to those that existed prior to the run.

1.4 System Requirements

You will need a personal computer operating under DOS. A 286 version system will suffice, although 386- or 486-class systems with math coprocessors will improve performance. A minimum of 2 megabytes should be available on the hard disk on which you will install CORRODE. The data that you define for each bridge, treatment, analysis, and report will require additional disk space.

You should be able to develop a set of several examples without any concern about disk space. However, before you input data for many bridges or build an extensive library of treatments that you will be applying in the future, you may want to consider the implications of these for disk storage requirements and plan your system installation accordingly.

1.5 Useful Keystrokes and Other Conventions

Standard keystrokes help you move about the CORRODE program, select options, and enter data. The list below describes standard keystrokes and typical situations in which you would employ them.

- **Navigating through menus and forms:** Use the up-down and left-right arrow keys in the normal way to move through a menu list or option list or across the main menu bar at the top of the screen. In a data input form, move between fields using up-down arrows; move within a field, from character to character, using the right-left arrows.

- **Selecting options:** When CORRODE provides a list of options and asks you to select one, move the cursor with the up-down arrow keys to your choice and make your selection with the Enter key.

- **Entering data:** When CORRODE asks you to enter data (whether alphanumeric, as for the name of a file, or numeric, as for bridge dimensions or corrosion data), it will provide a field for entry. Use the standard keyboard to enter or edit data and the left-right arrow keys to move about in the field. The backspace, delete, and insert/type-over keys should work normally. If a default entry (or your prior entry) is already

provided in the field, you may either accept this entry by pressing **Enter,** or you may clear the field by pressing **F6** and then enter new data. After data have been entered, press **Enter** to complete your entry.

- **Available fields:** most fields will appear in one color (cyan on color monitors), indicating that you may input or edit data therein. Fields of a contrasting color (e.g., red characters on black background) indicate that these fields are unavailable for input or editing. CORRODE controls the availability of fields to indicate valid options. Often it determines what fields are valid in response to information you have already provided.

- **Invalid entries:** If you make an invalid entry, CORRODE will issue a Beep. Please refer to the message at the bottom of the screen indicating what you should do next.

- **Context-sensitive help:** For each option or field, CORRODE displays a brief message indicating what you need to do next at the bottom of the screen. For more detailed information and assistance, press **F1.**

- **Finishing:** After you have selected options or input your data within a data form, you may save your work by pressing **F10.** If you wish to quit without saving any recent changes you may have made, press **Escape.** To exit any input form or menu with no action taken, press **Escape.**

- **Cannot close:** If you are trying to save your work (F10) or to quit (Escape) and CORRODE won't let you (accompanied by a Beep), this means that a field contains an invalid entry. Please be sure that all mandatory fields have valid data. Also, check the message bar at the bottom of the screen for hints on what needs to be done.

- **Exiting CORRODE:** When you are completely done with CORRODE and wish to quit the program, enter **Alt-Q.** If the system does not quit, press Escape one or more times to return to the main menu bar and press **Alt-Q** again. Please be sure, however, that you have saved all your work beforehand by using the F10 key.

A guide to typically required keys is displayed in a message bar at the bottom of the screen or at the bottom of data entry forms.

1.6 Screen Layout

CORRODE includes a number of different screen displays appropriate to the particular task at hand. Although they vary in appearance, they have some common features to help you use CORRODE more effectively:

- The main menu bar appears at the top of the screen after you have entered the system. It provides you access to the different parts of the CORRODE system and organizes system options and capabilities that are available to you. Chapter 2 describes the main menu bar in more detail.

- A series of information bars appears at the bottom of the screen, identifying current system selections and providing useful reminders. Different numbers of bars may appear at different times. From the bottom up, the information displayed in these bars includes the following:

  1. **Current selections:** e.g., the current user id, the selected bridge, relevant treatment file, relevant corrosion file, etc. (Not all of these will appear at the same time.)

  2. **Useful function keys:** general keystrokes to help you with the current operation (e.g., F10 to save or complete a task; Escape to quit; F6 to clear a field; etc.). Entries in this bar will change with the task at hand.

  3. **Brief instructions:** a message informing you what needs to be done, or input based on the current location of the cursor.

  4. **Status message:** a message informing you of the current status of the system (e.g., the successful completion of a task). This bar will appear only when necessary.

1.7 Additional Notes Before Starting

Required Data and Default Values

CORRODE is based on a technical analysis of bridge deck corrosion and related distress and an economic evaluation of different protective or corrective strategies, which have been developed. The system requirements for data input conform to these technical and economic analyses, as described in Part I of this document. Guidelines governing required data and default values are as follows:

- The data requested in CORRODE's input forms should be interpreted as "required," whether for an analysis or for file identification. The only exceptions are comment fields, which are for your convenience; they are always optional, never required.

- CORRODE uses two mechanisms to guide your input of data so that it is relevant to the specific conditions and point in the history of each bridge deck:

1. CORRODE controls access to the input fields, allowing you to provide input only to those fields that are relevant. Fields that are not relevant appear in a contrasting color, and you are blocked from entering data in these fields.

2. CORRODE determines the appropriate input forms to display, based on data input to that point. For example, forms to accept values of certain data are displayed only if you indicate that such data are available. Also, the display of certain input forms for corrosion data is predicated on CORRODE's analysis of whether or not corrosion has already taken place in the bridge deck.

- Default values are provided as the initial display of input forms. These values have been selected so as to be "transparent" to any analyses that you may run (i.e., they will not interfere with or contradict any of your assumptions). These values are "null" values — i.e., they make no assumptions one way or another, and are generally zeros (for input variables) or assumed values (e.g., for coefficients or exponents in formulas).

- "Example" files are provided if you wish to see how a problem can be structured. These files contain realistic values of input data for a particular problem and can be run directly to see how CORRODE's analyses perform and to inspect its reports and graphs. However, as with any example, these assumed values reflect particular bridge design characteristics, materials properties, history, cost of protective or corrective strategies, etc. These values are meant to illustrate CORRODE's features, not to serve as general values for all bridge decks. It remains your responsibility to ensure that the values entered in CORRODE's input forms are realistic for each bridge deck being analyzed.

- To ease the burden of data input for large numbers of bridges, you may take advantage of CORRODE's input features to define your own libraries of default values: e.g., for particular classes (or designs) of bridge decks, for particular years of construction or for particular regions in your state. These user-defined files may then contain appropriate "default" values that can be tailored for each individual bridge deck.

- CORRODE is structured to allow flexibility and choice in the analyses you perform. The data that are "required" depend, of course, on the types of analyses to be performed. For example, if you wish to perform only a corrosion analysis, but not to analyze life-cycle costs, then only the data related to corrosion would need to be input — the data in the life-cycle cost menu would not be required at that time. Or, if you wish to analyze life-cycle costs based only on agency costs, not bridge user costs, then the key inputs for bridge user costs could be specified as zeros.

Default values and example values for each data input form are included in Appendix A.

CORRODE Subdirectories and Files

The installation procedure sets up a set of subdirectories and files needed to store data, define required defaults, and manage the file structure. With the exception of SETUP.PRN already discussed for the printer, please **do not** modify or delete any of CORRODE's file system through DOS; errors in system operation will likely result. Any changes to files should be accomplished only through the commands and options provided by CORRODE itself, as described in Chapters 6 and 7.

In addition to the printer files SETUP.PRN and RESET.PRN already discussed, CORRODE also maintains a file BREXT.ZZZ in the CORRODE directory. This file keeps track of the sequence of bridges already defined and enables CORRODE to know the sequence number of the next bridge to be defined. An unauthorized modification of this number will corrupt CORRODE's ability to manage the list of defined bridges in its files and may result in loss of data and unpredictable errors in operation.

A series of files is maintained by CORRODE in the PARAM, MODEL, and REPORT subdirectories within CORRODE. These files store several types of data: input values that you provide, results of CORRODE's analyses, formatted reports, and tracking information needed for file management. **No changes to these files should be made through DOS.** Please use only the commands provided in the CORRODE menu structure to accomplish needed changes in these files.

2. Getting Started: The Main Menu

2.1 CORRODE Title Screen

Short Explanation

After the CORRODE system is installed, you may start it by typing **corrode** in the directory in which the system is installed. The system will respond by displaying a title screen.

The screen asks you to enter your initials (three maximum). These initials will be used to label and manage files containing input data, results (e.g., reports, graphs, logs), and other information that is produced by the system. Enter your initials and press **Enter.** The system will automatically display the main menu.

More Advanced Notes

The initials that you enter on the title screen when you start CORRODE identify you as a "user" to the system. Your files will be kept separate from those defined by other users. When you use the system, you will be able to list only those files that are assigned to you; you will not have access to files created by other users. You and other users should therefore observe the following protocols:

- Each user of CORRODE should be identified by a unique set of initials. For example, if both Mary E. Jones and Mike E. Jacks will be using the system, they should agree on unique identifiers for each: e.g., MJ vs. MEJ; MJ1 vs. MJ2; or any other distinction (e.g., ABC vs. XYZ).

- Different users may define files of the same name; CORRODE will still regard these files as separate, distinct, and independent of each other. For example, users ABC and XYZ could each define a bridge file named BRIDGE. CORRODE will treat these files (and all derivative files) as separate entities. ABC will be able to list, edit, and use only the BRIDGE file that ABC has created; likewise, XYZ will be able to list, edit, and use only the BRIDGE file that XYZ has created.

Organizations may use this feature to their advantage. For example, the system of initials does not need to be limited in concept to individual users. Different initials could be defined to stand for different organizational units (e.g., different districts) or geographic or other breakdowns (e.g., EST could encompass all bridges in the eastern part of a district or state; WST, the western part; etc.).

2.2 Main Menu

The CORRODE main menu is displayed in a bar across the top of the screen. Each entry in the main menu corresponds to a major set of CORRODE system operations that are described in later sections of this manual. The main menu options are illustrated in Figure 1 and are described below:

- The BRIDGES option is used to build and edit files containing general information about a bridge and to select a particular bridge deck to be analyzed.

- The TREATMENTS option is used to build and edit files containing information about a deck treatment.

- The ANALYSES option is used to invoke two types of analyses in CORRODE: (1) the current state of corrosion and corrosion-related distress in the bridge deck; and (2) a life-cycle cost analysis of one or more treatments preventing or correcting corrosion-related distress, to determine the optimal time and cost of each.

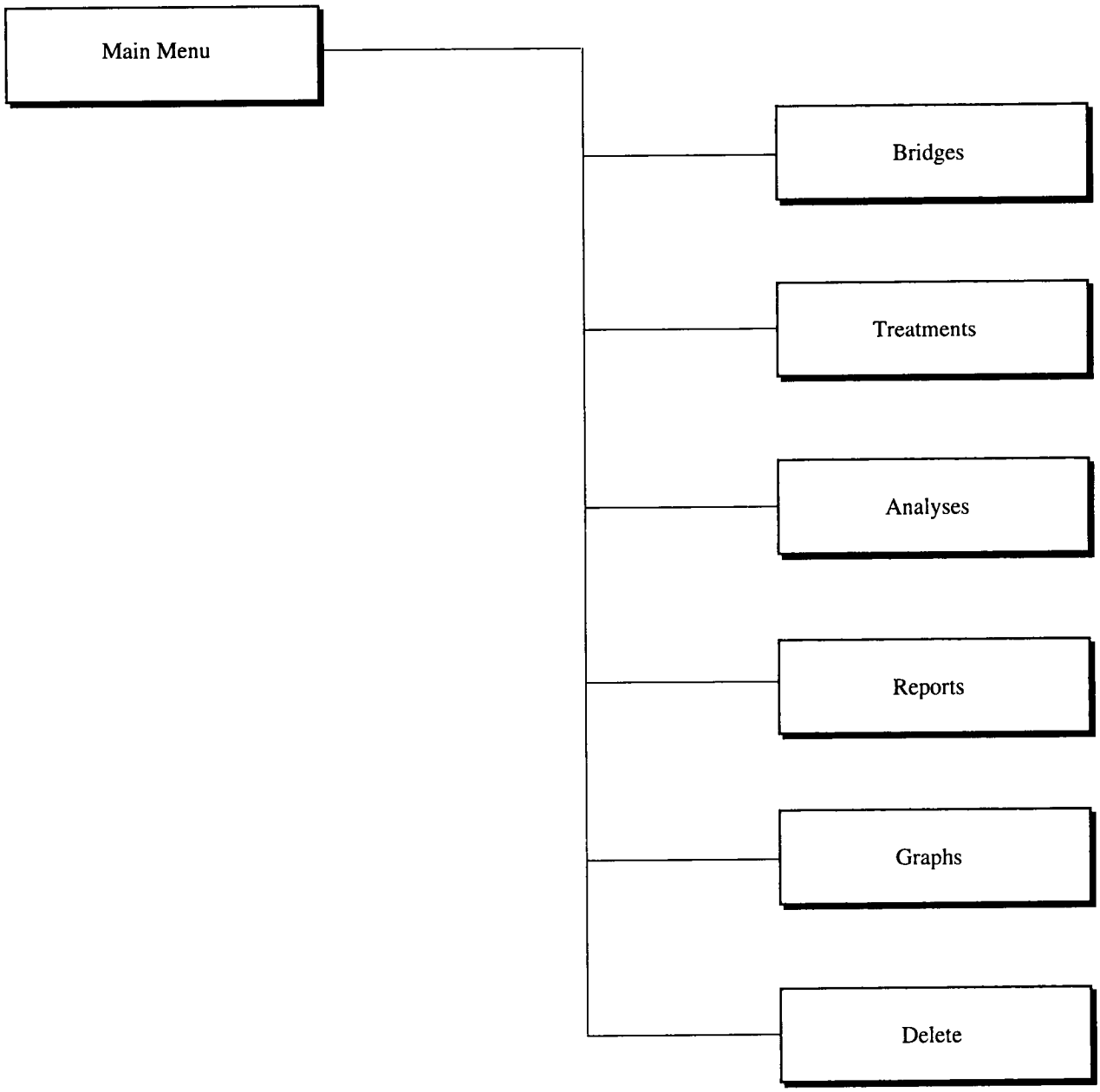
- The REPORTS option is used to select and display different types of reports available from CORRODE. These reports encompass the results of both the corrosion and the life-cycle cost analyses.

- The GRAPHS option is used to display screen graphs of the life-cycle cost results.

- The DELETE option is used to manage files: that is, to discard bridge, treatment, corrosion, or life-cycle cost files that are no longer needed.

Selections in the main menu may be made by moving the cursor with the left or right arrow keys. (You may also press the Escape key as many times as necessary to eliminate any pull-down menus, and then type the first character of the desired selection: e.g., "T" for TREATMENTS, etc.)

Figure 1. Main Menu Options



2.3 Quick Tour

The main menu allows considerable flexibility in building, analyzing, and reporting a life-cycle cost analysis of different bridge deck treatments for corrosion. A typical (but by no means the only) order in which the main menu items can be accessed is given below. You should not feel confined by this example, however; more general rules on how to proceed through the main menu are given later.

A typical sequence of main menu selections might proceed as follows:

- First, complete the description of a bridge structure in the BRIDGES block.
- Second, define one or more treatments in the TREATMENTS portion of the menu.
- Third, run a corrosion analysis in the ANALYSES portion of the menu. If desired, obtain a corrosion-related report afterward by calling up the REPORTS menu.
- Following the corrosion analysis, run a life-cycle cost analysis of one or more of the treatments that have been defined, again in the ANALYSES portion of the menu.
- View the results of the life-cycle cost analyses in graphs on the screen, using features provided in the GRAPHS option.
- The graphs may suggest particular reports that would be most useful to obtain and which may be selected in the REPORTS block.
- Results needed for future reference may be retained. Other files may be deleted using the DELETE options.

This sequence of operations provides a logical order in which to use the features in CORRODE to address a realistic problem. In fact, it is very typical of how an agency might use CORRODE if it were analyzing a very small number of bridges or looking at bridges one at a time. In other cases, however, more flexibility may be needed — e.g., to input information for several bridges at a time, or to describe several treatments at a time. Descriptions of bridges or treatments that were entered previously may need to be updated with more recent or more accurate information. CORRODE allows the flexibility to approach problems in different ways, subject to the following general guidelines:

- The BRIDGES and the TREATMENTS options may be entered in any order and any number of times. Several bridges may be defined first, then treatments or vice versa. Data entered previously may be edited at any

time. However, a BRIDGE file and a TREATMENT file must be completed before they are used in any of the ANALYSES.

- To identify which bridge should be studied when specifying a corrosion analysis or a life-cycle cost analysis in the ANALYSES option, the bridge must be "selected." Bridge selection is also necessary when defining treatment files. Bridge selection is made in the BRIDGES option.

- The corrosion analysis of a bridge must be completed prior to a life-cycle cost analysis of that same bridge in the ANALYSES option. The life-cycle cost analysis also requires that you have already selected a bridge for analysis in BRIDGES and that you have already defined a treatment in TREATMENTS.

- Once both the corrosion and the life-cycle cost analyses are run, you may request displays of these results at any time thereafter, using the REPORTS and the GRAPHS options. Reports and graphs may be obtained at any time, so long as the results files for the particular runs are retained.

- Files that **are not** to be retained can be deleted using the procedures in DELETE.

As you become more familiar with the system, you will be able to use these guidelines to advantage. For example, you may begin building a library of information about your bridge inventory by creating a bridge file for each deck that you may wish to study. You may also wish to create a "standard" hypothetical bridge to which you attach "standard" definitions of treatments that can later be copied and tailored to specific decks. Ultimately, you may want to test several treatments at one time so that you may compare their life-cycle costs and recommended time of performance. All of these objectives can be accomplished by using the system's features described in later chapters.

These guidelines provide a general overview of system capabilities and the typical order of steps that you may follow. Details on each option in the main menu are presented in later chapters, as follows:

- Chapter 3 discusses bridge descriptions and other capabilities of the BRIDGES options.

- Chapter 4 explains how to define treatments using the TREATMENTS options.

- Chapter 5 covers both the corrosion analysis and the life-cycle cost analysis that are provided in ANALYSES.

- Chapter 6 describes how analysis results may be displayed, using features in REPORTS and GRAPHS.

- Chapter 7 covers DELETE and other aspects of file management in CORRODE.

3. Bridge Descriptions

3.1 Overview

The description of general bridge characteristics and their selection for data input and analysis are handled through the BRIDGES option in the main menu. The BRIDGES submenu provides three options:

- Selecting a bridge;
- Editing a previously defined bridge file; and
- Creating a new bridge file.

These options are illustrated in Figure 2 and will be explained in more detail below. Following these explanations is a description of the basic information that you may input to the bridge file.

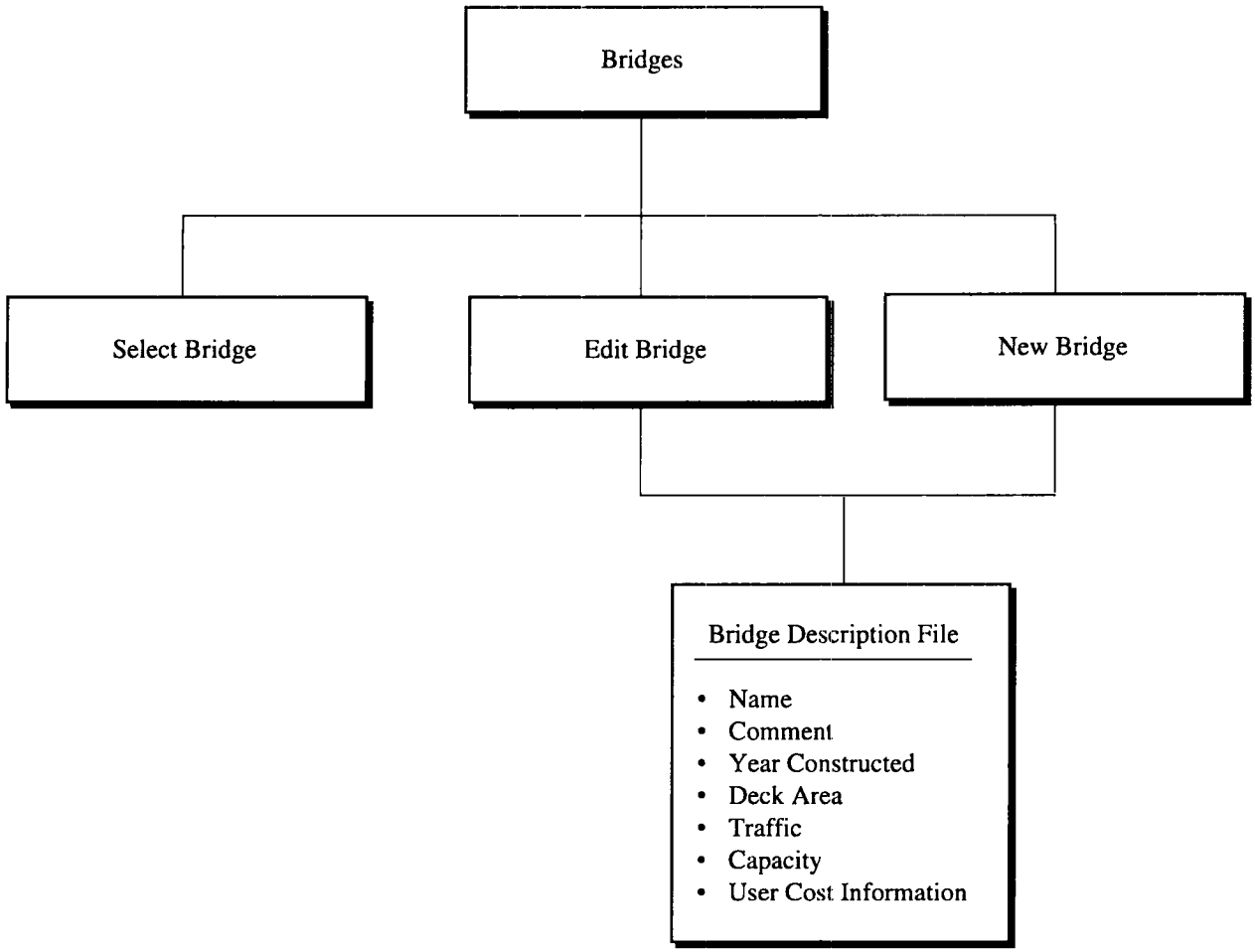
3.2 Selecting a Bridge

A bridge must be "selected" before its file can be edited or used in any analysis performed by CORRODE. A bridge must also be selected before other files relating to it (e.g., treatments, reports) can be defined or used, since these data must always be assigned to a specific bridge. In this way, it is always clear to you and to CORRODE which file is being edited or applied in an analysis, or to which bridge a file should be assigned.

The name of the selected bridge always appears in the information bar at the bottom of the screen, following the "Bridge:" tag. If this name identifies the bridge file you wish to work with, the bridge is already selected and you may proceed. If this name is different from the file you wish to work with, or if you are not sure and would like to check the names of the bridge files already defined, then choose the SELECT BRIDGE option:

- CORRODE will display the names of currently defined bridges (if any).
- Use the up-down cursor keys to scroll through the list until you find the bridge file name you wish to select.

Figure 2. Bridge Menu Options



- Press **F10** to complete the selection. The name of the selected bridge file will appear in the information bar at the bottom of the screen.

3.3 Editing an Existing Bridge File

You may edit an existing bridge file at any time to update information, complete a description you began earlier, or correct previous errors. However, the CORRODE system lets you edit only the currently selected bridge file. If the file you wish to edit is not currently selected, please refer to the preceding section on selecting bridges before you proceed with editing.

Once you have selected the correct bridge file, choose the EDIT BRIDGE option:

- CORRODE will display a blank window. You cannot enter anything in this window. This feature is to remind you that only the selected bridge can be edited.

- Press **F10** to continue editing, or **Escape** to quit (for example, if you need to select a different bridge).

- If you pressed F10 above, CORRODE will display the current contents of the selected bridge file, which you may then proceed to edit. Explanations of these data are presented later in this chapter.

- When your editing changes are completed, you may save them by pressing **F10**. Alternatively, you may press **Escape** at any time to exit the file without saving your most recent changes. (CORRODE will prompt you to be sure this is your intention.)

3.4 Defining a New Bridge File

You may add to the system's library of bridge files by defining new files. In this way, you can develop a set of files for all reinforced concrete bridge decks in your network that you may wish to analyze. To define a new bridge file, select the NEW BRIDGE option:

- CORRODE will respond with a window in which it asks you for a bridge file name. In some cases the name of the previously edited file may already appear.

- Edit this field to provide the name of the new file, and press **F10** to continue.

- Normally, the name you provide should be different from the names you have defined previously. If you enter a name that has already been defined, CORRODE will respond with a message asking, **OK to overwrite existing file?** If you respond no (N), CORRODE will return you to the entry field so that you may modify the name you had entered. If you respond yes (Y), CORRODE will display the current contents of the existing file you have specified, and the procedure from this point onward will be the same as if you had requested to edit an existing file.

3.5 Contents of the Bridge File

The contents of a bridge file are the same regardless of whether you are defining a new file or editing an existing one. The only difference CORRODE imposes on these two operations is that when defining a file for the first time, you specify its name; when you are editing an existing file, CORRODE displays the assigned name but does not allow you to change it. The reason for this feature is that the bridge file name is used as part of the DOS file name for these bridge data as well as for other data files. To maintain orderly file management, CORRODE retains a bridge file name unchanged once it is assigned.

The items within the bridge file are as follows:

- **Bridge name:** the name that you assign to the bridge file when you first define it. The name is limited to eight alphanumeric characters and must conform to DOS file-naming conventions. Typically this name relates to the name of the bridge that is represented.

- **Comment:** a text field in which you may enter any descriptive information, to a maximum length of 64 characters. This information is not used by the CORRODE system in any way; it is strictly for your convenience. You may use this field to describe, for example, more detailed information about the bridge deck in question, notes on current deck condition, the date and findings of the most recent inspection, or comments on the types of treatments you will be investigating.

- **Year (re)constructed:** the calendar year in which the deck concrete was placed as the result of initial construction or replacement.

- **Deck area:** the plan area of the bridge deck in square feet.

- **Traffic:** the two-way traffic volume, vehicles per day or annual-average daily traffic (AADT), through the analysis period. If traffic growth or decline is anticipated, enter the estimated average value over time.

- **Normal capacity:** the two-way capacity of the bridge, in vehicles per day or AADT, under normal operating conditions (i.e., with no construction zones or other temporary restrictions or devices).

- **Average crossing time:** the average time for a vehicle to cross the bridge, in minutes, accounting for the variation in traffic volumes throughout the day and year. For example, a weighted average of peak and off-peak conditions would suffice.

- **User cost coefficient:** the coefficient K_2 in the formula given below, representing average dollars per vehicle (accounting for the mix of vehicles in the traffic stream).

- **User cost exponent:** the exponent n_0 in the formula given below, representing the rate of increase of user costs with deteriorating condition of the bridge deck.

The user cost function for normal bridge conditions (i.e., in the absence of construction work zones or detours) is as follows:

$$U = K_2 \{S / S_m\}^n_0 \qquad \text{(Eq. 3.1)}$$

where

U = the incremental increase in user costs due to worsening deck condition, in dollars per vehicle, computed by CORRODE

K_2 = the unit user cost, in dollars per vehicle, that you input above

S = the bridge condition over time that will be estimated by CORRODE in the corrosion and life-cycle cost analyses

S_m = a technological maximum value of distress that you input in the ANALYSIS submenu (Chapter 5)

n_0 = an exponent controlling the growth of user costs with decreasing deck condition

This user cost identifies one benefit of keeping a bridge deck in good condition. The user cost is intended to reflect primarily travel time considerations and the avoidance of congestion costs that would otherwise be due to badly deteriorated decks. However, if you wish this function to represent other components of user costs for which you have estimates (e.g., vehicle wear and tear, safety-related costs), there is no reason why you could not include these considerations as well in your determination of the value of the unit user cost, k_2, above. If reflecting only travel time, K_2 should be based on an estimate of the value of travel time for the traffic stream and the uncongested speed (or travel time) across the bridge.

4. Description of Treatments

4.1 Overview

Treatments are activities performed on the bridge deck to address corrosion-related distress. These activities may be either preventive or corrective in nature, and may encompass different techniques (e.g., portland cement concrete (PCC) patching, overlays, sealers, cathodic protection). As new technologies become available, they may also be defined as treatments to investigate, for example, their potential cost-effectiveness.

In order to encompass a wide range of treatments, CORRODE adopts a flexible input format that asks you to describe the essential characteristics of a treatment — e.g., its nominal life, costs, the production rate at which it can be installed, and so forth. CORRODE does **not** ask you, however, to classify the treatment in any way — e.g., to group it as an "overlay" or a "sealer," for two reasons:

- Treatments can be defined as a combination of techniques: e.g., patching of distressed areas plus overlay or sealer applied over the entire deck area.

- As new methods are developed or experimental materials are tried, it may not be possible to classify them according to conventional techniques.

You must therefore ensure that the treatments specified are appropriate to the respective bridge deck and compatible with its elements and materials. Examples of compatibility considerations are given in Tables 1 and 2.

The data that describe a treatment are grouped in treatment files, much as the bridge descriptions are contained in bridge files. Procedures to create and edit treatment files are likewise similar to those for bridge files. The organization of treatment input options is illustrated in Figure 3. The following sections describe the options available in the TREATMENT submenu and the data contained in each treatment file.

The TREATMENT menu provides three options:

- Editing a previously defined treatment file,

- Creating a new treatment file,

Table 1. Selection of Compatible Deck Treatment Alternatives

Technical Disadvantage	Conc. Over.	AC Memb.	Seal. Coat.	Cathod. Protect.	Reason
Additional dead load critical	Not Good	Not Good		Not Good[1]	Overlays add to dead load[2].
Active cracks in conc.	Not Good			Not Good[3]	Active cracks reflect through concrete.
Existing overlay on deck		Not Good	Not[4] Good		Removal of old system results in rough surface[5].
Concrete surface scaled		Not Good			Rough concrete surface
Existing slotted cathod. protect.	Not Good				Scarifying concrete damages anodes
Existing polymer injection repair in concrete				Not Good	Insulated bars
Electricity not available				Not Good	Cathodic protection needs electricity
Skid resistance critical			Not Good[6]		Skid resistance may decrease
Steep grades and/or crossfalls	Not Good[7]				Concrete may flow after strike off
Sharp skew and/or curvature	Not Good				Difficult to pave with concrete finishing machines

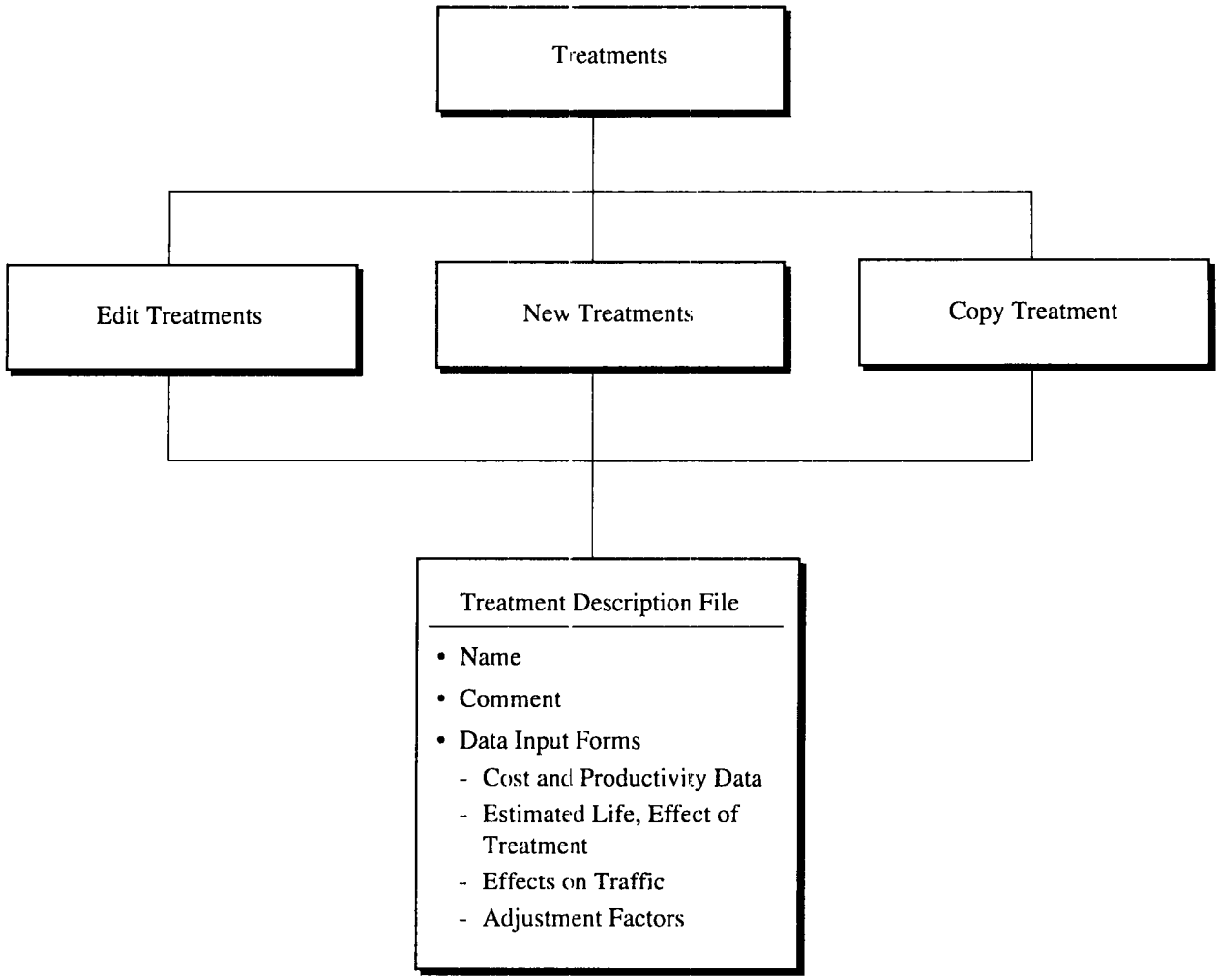
1. When cathodic protection is used with an overlay.
2. Unless, an existing overlay (or a layer of the concrete) is removed and replaced.
3. When cathodic protection is used with a concrete overlay.
4. May be applied on some concrete overlays.
5. Rough concrete surface can puncture membranes, unless a smooth concrete surface can be provided for the new membrane.
6. Exceptions can exist.
7. When slump is 4.5 inches (11.4 centimeters) or more.

Table 2. Selection of Compatible Structural Treatment Alternatives

Technical Disadvantage	Recast.	Preplaced Aggregate	Patch	Shot-crete	Cathod. Protect.	Reason
Repair depth more than 2 inches			Not Good	Not[1] Good		Concrete consolidation and bonding can be a problem
Small area repair				Not Good		Mobilization not justified
Internal vibration problem	Not Good					Concrete consolidation can be a problem
Experienced contractor not available		Not Good				Certain skills required
Electricity not available					Not Good	Cathodic Protection need electricity
Existing polymer injection repair in concrete					Not Good	Insulated bars

1. Shotcrete may be applied in several stages.

Figure 3. Treatment Menu Options



- Copying a treatment file defined for one bridge to allow you to apply it to another bridge.

These options are explained in more detail below.

4.2 Editing an Existing Treatment File

You may edit an existing treatment file at any time to update information, complete a description you began earlier, or correct previous errors. Choose the EDIT TREATMENT option in the submenu:

- CORRODE will display the names of currently defined treatments (if any).

- Use the up-down cursor keys to scroll through the list until you find the name of the treatment file you wish to edit. Select the treatment by pressing **Enter.**

- You may edit the name of the treatment file, as well as other data contained therein. Editing the name of the file has the same effect as creating a new file of that name. In this case the treatment file bearing the original name will remain unchanged when you complete your work. (This convention differs from procedures for bridge files in Chapter 3, in which names of current files cannot be changed.)

- When your editing changes are completed, you may save them by pressing **F10.** The name of the selected treatment file will appear in the information bar at the bottom of the screen. Alternatively, you may press **Escape** at any time to exit the file without saving your most recent changes. (CORRODE will prompt you to be sure this is your intention.)

- **Note:** Treatments are associated with specific bridges in CORRODE, since the data in a treatment file depends at least to some degree on the characteristics of the bridge to which it will be applied. When you edit a treatment file, it will be associated with the currently selected bridge. If you wish to edit a treatment associated with a bridge other than the one currently selected in the information bar at the bottom of the screen, return to the BRIDGES menu and select the desired bridge before editing the treatment. (Refer to Chapter 3 on how to "select" a bridge file.)

4.3 Defining a New Treatment File

You may add to the system's library of treatment files by defining new files. In this way, you can develop a set of files for relevant treatments to be considered for the inventory of bridge decks in your network. To define a new treatment file, select the NEW TREATMENT option:

- CORRODE will respond with a window in which it asks you for a treatment file name. In some cases the name of the previously edited file may already appear.

- Edit this field to provide the name of the new file, and press the **F10** key to continue.

- Normally, the name you provide should be different from the names you have defined previously. If you enter a name that has already been defined, CORRODE will respond with a message asking, **OK to overwrite existing file?** If you respond no (N), CORRODE will return you to the entry field so that you may modify the name you had entered. If you respond yes (Y), CORRODE will display the current contents of the existing file you have specified, and the procedure from this point onward will be the same as if you had requested to edit an existing file.

- **Note:** When you define a new treatment file, just as when you edit an existing file, it will be associated with the currently selected bridge. If you wish the treatment to be associated with a bridge other than the one currently selected in the information bar at the bottom of the screen, return to the BRIDGES menu and select the desired bridge before defining the treatment. (Refer to Chapter 3 on how to "select" a bridge file.)

4.4 Copying a Treatment File

Many times you may wish to apply a given type of treatment to more than one bridge deck. Ideally, you would like to be able to define a treatment only once, and then apply that information to any bridge deck for which the treatment may be applicable. In practice, however, this time-saving approach cannot be implemented so easily. The reason is that the information that describes a treatment depends at least to some degree on the characteristics of the bridge deck in question. For example, the productivity and costs of a treatment may depend on the area of the deck and how many lanes can be closed at once to perform work. These data also depend on when the estimate is made, since both productivity and cost vary over time as a result of technological advances, evolving legal requirements and standards of good practice, and cost inflation.

CORRODE provides a compromise between these two considerations by allowing you to copy a treatment file defined for one bridge to a new file to be applied to a different bridge. You may then modify whatever information, if any, needs to be changed to reflect the application of this treatment to the new bridge. In this way, the integrity of each bridge-treatment combination is maintained, but you have the flexibility to use previously defined treatments to the greatest advantage possible, without having to input the treatment descriptions anew for each bridge.

Select the COPY TREATMENT option in the submenu. CORRODE will provide you with a set of choices in sequence, as follows:

- First, specify the bridge from which you would like to copy the treatment. You might, for example, select a bridge whose location, size, structural characteristics, traffic, etc., match most closely the bridge in question. Or you might select a bridge for which the estimates of treatment costs, production rates, etc. are, in your opinion, the most current. Perhaps there is only one other bridge for which this treatment has been defined previously. (There is no requirement that you copy any previously defined treatment — you may elect instead to define a new treatment file from scratch, using the NEW TREATMENT option rather than COPY TREATMENT. The whole purpose of COPY TREATMENT is to make a time saving approach available to you in defining your set of treatments throughout the bridge network.)

- Next, CORRODE will ask which treatment you wish to copy from the bridge identified above. CORRODE will display a list of these available treatments, through which you may scroll using the up-down cursor keys. When you locate the treatment to be copied, press **Enter**. If you do not see the treatment that you intended to copy, you may press **Escape** to exit this set of submenus and try another approach (e.g., by selecting a different bridge for which to search the list of treatments, or by editing an existing treatment, or by defining a new treatment).

- Finally, CORRODE will ask you for the name of the file to which the selected treatment is to be copied. You may use the same name by which the treatment was known for the previous bridge, or you may change this name. Press **F10** to complete the copying operation; or you may press **Escape** at any time to quit without copying.

  Even if you select the same name as used previously, CORRODE will recognize the new file as a different file, since CORRODE associates treatment files with the specific bridges for which they are defined. For example, assume the currently selected bridge has the name CONCRETE. You wish to copy a treatment file OVERLAY defined previously for the bridge file named BRIDGE to use with bridge file CONCRETE. Using COPY TREATMENT, first select the bridge name BRIDGE, then the treatment name OVERLAY. When CORRODE asks you the name of the file to be copied to, you may select OVERLAY or any

other valid name. If you select OVERLAY, CORRODE will recognize that the OVERLAY file associated with CONCRETE is different from the OVERLAY file associated with bridge BRIDGE. You may therefore edit these two files independently of each other from this point on.

- Once a file is copied, you may edit it as you would any other treatment file. (Refer to the previous section on editing existing treatment files.) This allowance extends even to the name of the file. If you edit the name of a treatment file (plus any other data therein), it is as though a new file of the same name were defined. (CORRODE may provide you an informational message on this point, saying that a file originally defined for the former bridge has been "reassigned" to the latter bridge. This is for your information only and has no effect on the files in question.)

  As an illustration, consider the example above. Assume that you copy the BRIDGE / OVERLAY file into a new file CONCRETE / OVERLAY (where the slash denotes a bridge file / treatment file combination). You now edit the CONCRETE / OVERLAY file (since CONCRETE remains the selected bridge), but in so doing you also change its name to OVLY-1. When you are finished, CORRODE will associate two treatment files with bridge file CONCRETE: OVERLAY (which remains the same as when it was copied) and OVLY-1 (which reflects your editing changes).

4.5 Contents of the Treatment File

The contents of a treatment file are the same regardless of whether you are defining a new file or copying or editing an existing one. The items within this file are as follows:

- **Treatment name:** the name that you assign to the treatment file when you first define it or subsequently copy it or edit it. The name is limited to eight alphanumeric characters and must conform to DOS file-naming conventions. Typically, this name is a brief identification of the type of treatment that is represented. As noted earlier, treatments that are assigned to different bridges may have the same name; CORRODE will still regard them as different files, since CORRODE associates each treatment explicitly with the bridge for which it is defined.

- **Comment:** a text field in which you may enter any descriptive information, to a maximum length of 64 characters. The CORRODE system does not use this information in any way; it is strictly for your convenience. You may use this field to describe some technical information about the treatment in question, for notes on current treatment usage, or to identify treatment combinations represented by this file.

- **Technical and cost data:** the treatment file contains data in four broad categories, each associated with a separate data input form that is explained in the sections that follow. These data include (1) costs and productivities, (2) the estimated nominal life of the repair, (3) the effect of the treatment project on traffic flow, and (4) adjustment factors.

- **Viewing the data input forms:** you may view the data input forms for each of the sets of technical and cost data by moving the cursor to the respective line on the TREATMENT input submenu and pressing any key when the cursor is on the respective "button" for that form. (The "button" is displayed as a field with a "Y" in it.) When you complete data input, press **F10** to close a data input form, save any changes you have made, and move to the next button on the submenu. (Pressing **Escape** instead will also close the data input form but will not save your changes. CORRODE will return you to the same button on the TREATMENT submenu. When you press any key thereafter, the same data input form will again be displayed.)

- **Navigating the data input forms:** you may move through the fields of the data input forms by using the up-down cursor keys or the tab and shift-tab keys.

The following sections describe the information contained in each of the TREATMENT data input forms.

Cost and Productivity Data

You will use the first TREATMENT data input form to describe the cost and time (or productivity) to perform the treatment. Cost and productivity data are organized in parallel lists of cost components and time or productivity components. CORRODE will compute the total cost and total time required for a treatment as the sum of the contributions from each of these components. Costs will be tallied as part of the agency costs to be accounted for in the life-cycle cost analysis. The time required for a treatment will influence the estimate of the duration of traffic disruption, thereby affecting the incremental user costs during the project period that will also be accounted for in the life-cycle cost analysis. Data should be entered only for those cost and time components that are deemed relevant to the particular treatment being defined. If cost and time components are not relevant, a zero should be entered for both.

The discussion below refers to various measures of bridge deck condition or distress. Technical explanations of these are given in Chapter 5 in the discussion of corrosion and life-cycle cost analyses.

- **Fixed cost and time required:** fixed items of the project are those items whose time and cost are not a function of the deck area or amount of distress to be repaired. The cost is entered as a lump sum, in dollars. The

time is entered in days. (Include a time estimate only if the activity causes a restriction to the normal flow of traffic across the bridge.) Examples of items that can be included here are mobilization and setup of traffic controls.

- **Deck cost and productivity:** components of cost and productivity related to any work that will be performed on the total area of the deck: e.g., placement of a sealer or an overlay over the entire deck area. The unit cost entered here is in dollars per square foot of deck area; the productivity is expressed in square feet accomplished per day. For example, assume a deck area of 4,000 square feet. If an activity has a productivity of 200 square feet per day, the total time estimated for this activity will be 20 days. If the cost is $25.00 per square foot, the total cost estimated will be $100,000.

- **CL cost and productivity:** components of cost and productivity related to work to address only those areas of the deck that are chloride contaminated. The unit cost entered here is in dollars per square foot of chloride-contaminated deck area; the productivity is expressed in terms of square feet per day, applied only to the chloride-contaminated area. CORRODE computes the estimated area of chloride contamination over time in the life-cycle cost analysis (Chapter 5).

- **DL cost and productivity:** components of cost and productivity related to work to address only those areas of the deck that are delaminated (excluding spalls). The unit cost entered here is in dollars per square foot of delaminated deck area; the productivity is expressed in terms of square feet per day, applied only to the delaminated area. CORRODE computes the estimated area of delamination over time in the life-cycle cost analysis (Chapter 5).

- **SP cost and productivity:** components of cost and productivity related to work to address only those areas of the deck that are spalled. The unit cost entered here is in dollars per square foot of spalled deck area; the productivity is expressed in terms of square feet per day, applied only to the spalled area. CORRODE computes the estimated area of spalling over time in the life-cycle cost analysis (Chapter 5).

- **Maintenance cost:** the average annual cost of maintaining the treatment installation (not the bridge deck itself), in dollars per square foot. (This feature is intended to be applied to treatments like cathodic protection, which may entail periodic maintenance.)

Estimated Life and Effect of Repair

You will use the second TREATMENT data input form to describe the effect of the treatment on bridge condition. Specific data inputs are as follows:

- **Effect on chloride, delamination, or spalls:** CORRODE provides three "Yes-No" toggle switches by which you indicate the types of distress affected by the treatment. If you input Yes (Y) for one or more of these effects, CORRODE will prompt you for additional information in the next group of items. If you indicate No (N) for any item, CORRODE assumes that the treatment has no effect on that particular distress component. If you indicate No (N) for all three categories of distress, CORRODE interprets this treatment as a preventive activity, and will handle it as such in subsequent analyses.

  Note: preventive activities can be applied only before the time of initial corrosion at the level of the deck rebar. If, in the corrosion analysis, CORRODE determines that you have specified a preventive treatment and that corrosion has already begun, it will display a message informing you of this conflict and suggesting that you either check the corrosion input data or specify a corrective rather than a preventive treatment.

- **CL, DL, and SP following treatment:** three separate inputs describing, respectively, the percent of deck area that following repair is chloride contaminated, delaminated, and spalled. These inputs collectively represent your best judgment of how the repair affects the condition and future performance of the deck. For example, if patching will repair spalls but will not remove the existing chloride contamination or address delaminated areas, you would input zero for "SP following treatment," indicating that the treatment corrects the current spalling. You would then input a nonzero value for chloride and delamination following repair, reflecting the likely amounts of these distresses at the time of repair. For purposes of this analysis, the percent area of chloride contamination is that portion of the deck in which the rebar level chloride exceeds 0.035 percent by weight of concrete.

  This feature may also be used to reflect the quality of work or the reliability of the treatment. For example, if delaminated areas are to be patched, but experience indicates that only 90 percent of the delaminated areas are reliably detected at the time of repair, then "DL following treatment" would be input as 10 percent rather than zero.

- **Nominal life:** the estimated life of the treatment, in years, based on your experience and judgment. This nominal life establishes an upper bound for CORRODE's assessment of the actual predicted life of the treatment. The actual prediction will be based on considerations involving the corrosion

rate model, which may reduce the estimated life below the value you input but will never increase it. If you have no information on the nominal life of the treatment, estimate this value using the methodology developed in the report for SHRP Project C-103.[4]

- **Corrosion model:** the change in the corrosion rate that is effected by the treatment. These changes are characterized numerically by a "K" factor that is explained in the next item. Five options are specified for your selection: (1) the corrosion rate continues to increase at the same slope as prior to the treatment (K=1); (2) the corrosion rate continues to increase, but at a lesser slope than prior to the treatment (0<K<1); (3) the corrosion rate remains at the level that existed just prior to the treatment and neither increases nor decreases with time (K=0); (4) the corrosion rate declines somewhat from the level that existed prior to the treatment (K<0); or (5) the corrosion rate reduces to zero for some period of time (refer to the "Life with no corrosion" input item below). To a large degree, this selection depends on the impact of the treatment on the chloride concentration in the concrete and its effect on the rebar.

- **K factor:** a quantification of the change in corrosion rate indicated by your selection of a corrosion model above. K is defined as the ratio two slopes in the corrosion rate curve: the ratio of the slope after the treatment to the slope before the treatment. In some instances CORRODE will set the value of K automatically, based on your selection of a model (e.g., for K=0 or K=1). Where a range of K values is implied (i.e., K<0 or 0<K<1), input a value that represents your best estimate of the effect of the treatment on the rate of corrosion.

- **Life with no corrosion:** if corrosion model 5 is selected above, you have indicated that the corrosion rate reduces to zero. You must also then input the estimated time, in years, that the deck will experience no corrosion. This feature is intended for use with techniques like cathodic protection. (If you selected an option other than number 3 above, CORRODE does not permit you to enter a value in this field.)

Effect on Traffic

Treatments not only affect the condition of the bridge deck; their performance may also affect the traffic using the bridge, particularly if a work zone is established that restricts capacity or if a detour is necessary. This TREATMENT input form requests information that CORRODE will use to assess impacts to users and related increases in user costs due to a treatment project.

- **Traffic impact:** the type of impact that will result from the treatment, depending on how you envision the work will be performed. Two options

are specified: "congestion" or "detour." (If you anticipate no congestion — i.e., if the treatment requires no work zone or other reduction in the bridge's capacity — select "congestion" and follow the additional instructions below.)

Note that you may investigate different ways of performing treatments: e.g., closing one lane at a time, versus closing a few lanes at the same time, versus closing the entire bridge. These options can be defined as separate treatments, analyzed, and compared in terms of their relative costs to the agency and to bridge users.

Congestion

If "congestion" is selected above, you will be prompted for the following information relating to the congestion formula described below:

- **Unit user cost:** the cost coefficient (K_1 in the formula below), expressed in dollars per minute per vehicle. This value would be derived from an estimated value of time for the mixed traffic stream on the bridge. (If no congestion will be caused by the treatment, or if you do not choose to compute user costs in your analysis, enter zero.)

- **Congestion formula coefficient:** a calibrating constant (alpha in the formula below).

- **Congestion formula exponent:** a calibrating constant (beta in the formula below), with a value greater than 1.0.

- **Capacity during project:** the reduced bridge capacity due to imposition of a work zone, expressed in vehicles per day or annual-average daily traffic (AADT). This value should not exceed the normal capacity for this bridge that you input in the BRIDGES option. (If the treatment will have no effect on traffic flow on the bridge, you should make this value equal to the normal capacity you input in BRIDGES.)

The congestion formula for use during treatment projects in CORRODE is:

$$U_1 = K_1 \alpha t_f \left[\left(\frac{q_0}{C_1}\right)^{\beta} - \left(\frac{q_0}{C}\right)^{\beta}\right]\left[\left(\frac{DS_{t*}}{P_r}\right) + M\right] \qquad (Eq.4.1)$$

where

U_1 = the increment in bridge user costs during the project period due to congestion caused by the treatment work zone, in dollars per vehicle

K_1 = the value of bridge user time while traveling, expressed in dollars per minute per vehicle, averaged over the daily traffic stream

α = a constant with a default value of 0.15

t_f = the free-flow travel time across the bridge, in minutes

q_o = the average two-way traffic volume across the bridge, in vehicles per day

C = the two-way capacity of the bridge during normal (i.e., non-project) periods, in vehicles per day

C_1 = the two-way capacity of the bridge during the project period for the treatment, in vehicles per day (accounting for typical lane closures throughout the project and assuming the typical pattern of peak-hour and off-peak demand)

β = an exponent with a default value of four

D = the total deck area, in square feet

$S_{t\bullet}$ = the index of deck area distress at the time of the treatment

P_r = the productivity of the treatment, in square feet per day

M = a fixed time, as for mobilization, in days

This formula estimates incremental user costs due to congestion that will be incurred by the traffic stream for the duration of the treatment. The degree of congestion is sensitive to traffic volume and the relative reduction in capacity due to the treatment work zone. The duration of the treatment is a function of the distressed area and the productivity of the treatment. (This formula simplifies the actual calculation somewhat, since the actual calculation accounts for individual components of distress, as well as for overall deck treatments, and their respective contributions to overall duration of the treatment. The basic idea behind these calculations, however, is illustrated in the above formula.)

While Eq. 4.1 provides a correct conceptual treatment of congestion, it is an approximation, since it is based on daily rather than hourly traffic estimates. Calibration of the constants α and β should take this fact into account, together with the characteristics of the particular bridge and type of project work zone envisioned: e.g., the number of through lanes, lane width and side friction, whether one-directional or two-directional flow is affected, and anticipated degree of congestion. Literature on the value of drivers' time and operational characteristics of highway work zones provides

information that can help in these estimates. The default values cited above represent the case of restricted, but not heavily congested, flow through a work zone. The default value of β (4.0000) is based upon regression analyses of curves for such flows developed in a recent FHWA study.[9] The default value of α (0.15) is based on the premise that the value of travel time itself varies as a function of the length of delay, and that for increments of time of less than 5 or 10 minutes' difference, the value of time decreases to 15 percent or less of nominal value.[10] Other values of these constants can be provided for different situations:

- For situations in which restricted flows may result in delays exceeding 5 to 10 minutes, α may be increased to values of 1.0. to 3.0 or more.

- For situations in which heavy congestion is anticipated (involving significant stop-and-go cycles and attendant delays), the parameters α and β can be further adjusted to fit curves for congested flow such as those illustrated in reference 9.

Please refer to references 9 and 10 for examples of curves illustrating these effects.

Note also that you input the data used in Eq. 4.1 at different times, in different files:

- Data related to the bridge itself, but independent of treatments, are input in BRIDGES: e.g., the deck area and the normal traffic capacity of the bridge.

- Data dependent on the particular treatment specified (as well as on the bridge to which the treatment may be applied) are input in TREATMENTS: e.g., the restricted capacity of the bridge and the treatment productivity (which may depend upon the type and size of the work zone contemplated).

Detours

If "detour" was selected earlier, you will be prompted for one item of information: the average detour time per vehicle, in minutes. This value should reflect the incremental increase in travel time caused by the detour, averaged throughout the day to account for variations in flow and congestion.

Adjustment Factors

Adjustment factors were discussed in the early stages of CORRODE system design as a means to perform sensitivity analyses automatically. As of now they are not implemented.

5. Analyses

5.1 Overview

CORRODE includes two basic capabilities to help you analyze bridge deck condition and treatments:

- A **corrosion** analysis which considers inspection data and observations of the bridge deck concrete, estimates key corrosion-related parameters and the current condition in terms of a distress index, and uses a deterioration model to predict the change in distress index over time.

- A **life-cycle cost analysis** which considers the deck deterioration model estimated above, together with predictions of agency costs and bridge user costs associated with a treatment, to estimate the life-cycle costs of that treatment. These life-cycle cost estimates yield the optimal time of treatment performance, when life-cycle costs are at their minimum.

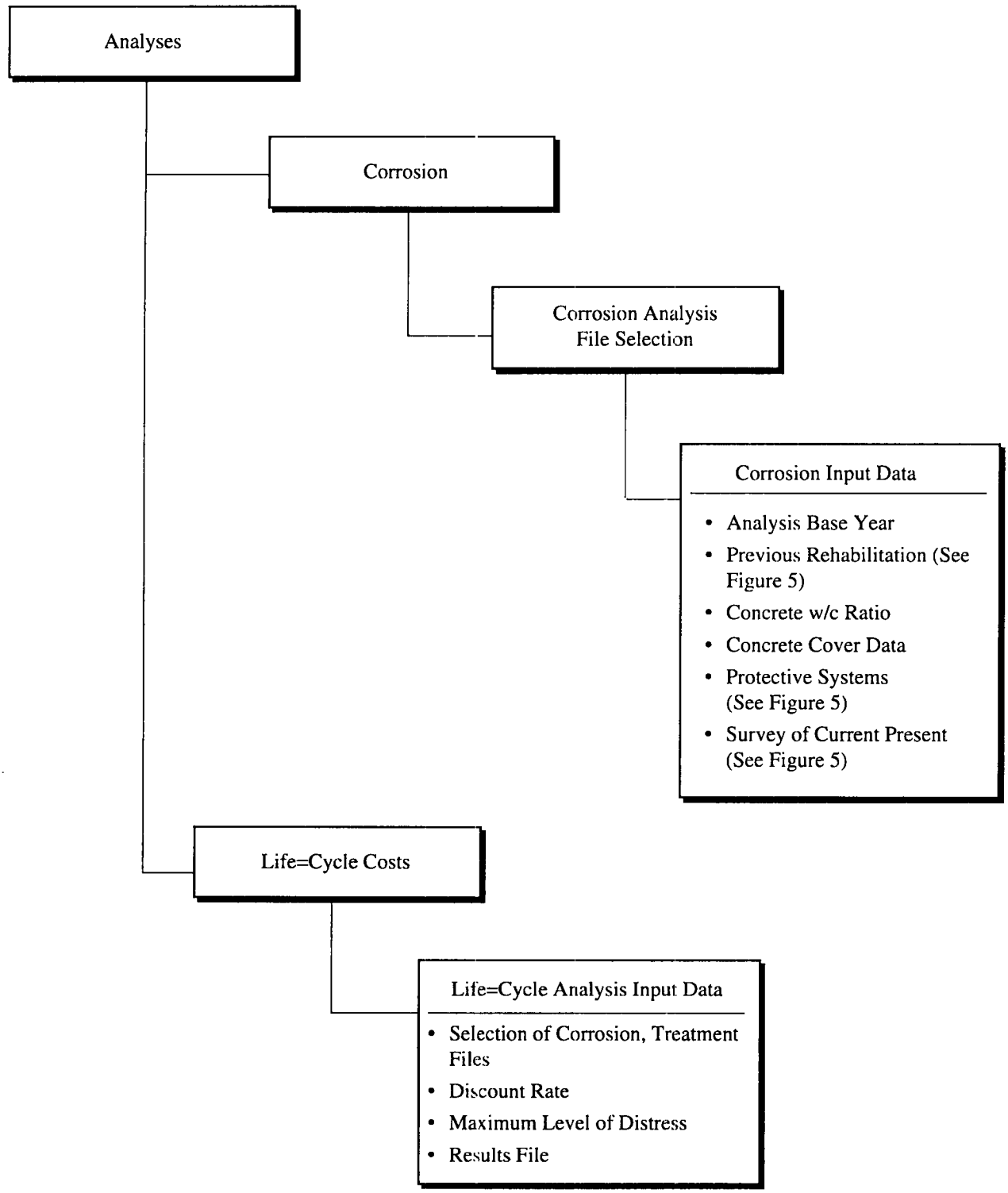
These two analyses are handled as distinct steps in CORRODE, as illustrated in Figure 4. Since a life-cycle cost analysis requires the results of a corrosion analysis, the corrosion analysis must precede any life-cycle cost run that refers to it. Beyond this basic rule, however, you have considerable flexibility in how you organize your analyses. You may run several life-cycle cost analyses based on a corrosion analysis (e.g., to test different treatments). If you receive an error message after a life-cycle analysis that suggests going back to the corrosion data, you may do so, make any corrections needed, and then repeat the corrosion analysis and any life-cycle cost analyses that depend on it.

The analyses are selected in the ANALYSES pull-down menu. Details on how to proceed through each analysis are given in the following sections.

5.2 Corrosion Analysis

Note: the corrosion analysis always applies to the "selected" bridge: i.e., the bridge identified in the information bar at the bottom of the screen. If the bridge you wish to study is not currently selected, go to the BRIDGES option and select the desired bridge before proceeding with the corrosion analysis. (Refer to Chapter 3 for how to select a bridge.)

Figure 4. Analysis Menu Options



Corrosion Analysis File Selection

Once you have entered the corrosion analysis submenu, CORRODE prompts you for the names of two files:

- **Start with:** choose any previous corrosion file that you may have used for this bridge which you would like to use as a point of departure in the current analysis. For example, if you performed a corrosion analysis with CORRODE for the selected deck a year ago, and you would now like to update those findings, choose the file pertaining to that run. If this is the first time you are analyzing a deck, or you don't wish to select any of the previously defined files, select the default.

- **Results file:** the results of the current corrosion analysis will be stored in the file you identify here. Choose a name that conforms to DOS-naming conventions. If the name you enter matches that of a previously defined corrosion file, CORRODE will ask you, **"OK to overwrite existing file?"** If you respond no (N), CORRODE will return you to the entry field so that you may modify the name you had entered. If you respond yes (Y), CORRODE will display the current contents of the existing file you have specified, and the procedure from this point onward will be the same as if you were editing the existing file.

The results file will be assigned specifically to the selected bridge. Thus, it is possible to have corrosion files of the same name assigned to different bridges. CORRODE regards these files as separate, independent files and keeps track of which corrosion files are assigned to what bridges. The name of the currently selected corrosion file appears in the information bar at the bottom of the screen, to the right of the selected bridge file.

Corrosion Input Data

Once file names are chosen, CORRODE displays the input data in the "start with" file. You may edit these data, and the results will be stored in the "results file." The input data are as follows:

- **Analysis base year:** the calendar year for which the corrosion analysis results will pertain. Generally this would be the current year.

- **Maximum distress:** enter the maximum level of distress that can occur before some remedial work absolutely must be done. This input, referred to as S_m in Part I of this document is intended to provide an absolute upper bound to the level of distress that will be accepted in the analysis performed by CORRODE. It is **not** indicative of a standard or of your department's practice, nor is it the level at which you think a treatment

should be done. Given its intended meaning, a deck will likely be repaired before this threshold is reached. CORRODE will restrict the solution according to this maximum: i.e., it will not allow the deck condition to worsen beyond this threshold, and it will force a treatment at that time.

- **Previous rehabilitation:** enter Y if the deck has been previously rehabilitated, N if it has not. If your response is yes, a separate input form will be displayed, as described in a section below. Also, if yes is entered, CORRODE suppresses certain other data items in the input form, since they will not be needed in the corrosion analysis.

- **W/C deck concrete:** enter the water-cement ratio of the deck concrete as a decimal fraction.

- **Number of cover data:** enter the number of cores taken to determine thickness of the concrete cover over the rebar. After you enter this number and press **Enter,** CORRODE displays an input sheet in which you enter each thickness observation, in inches. CORRODE will use this information to compute the mean and standard deviation of the thickness distribution and the estimated thickness at the 90 percent confidence limit. When you have finished entering the thickness data, press **F10.**

- **Protective system:** indicate (N or Y) whether a protective system has been installed previously for this bridge deck. A protective system significantly reduces the rate of ingress of chloride ions into concrete. Protective systems are limited to those decks that are **not critically contaminated** with chloride. Sealers, coatings, and polymer overlays are normally thought of as protective methods. However, hydraulic cement concrete overlays such as low slump dense, micro-silica, and latex-modified concrete can also be used as protective methods. If your response is Y, a separate input form will be displayed, as described in a section below. (Refer to the section below for a list of installed techniques that are included as protective systems in CORRODE.)

- **Present Condition:** indicate (Y or N) whether the data on the deck are from a survey of the condition with respect to corrosion. If your response is Y, a separate input form will be displayed, as described in a section below.

Three specialized input forms are mentioned above, dealing with previous deck repair, protective systems, and present condition survey data, respectively. These additional data input forms are shown schematically in Figure 5. Details on these are presented in the sections below.

Note: Several data collection and testing procedures are alluded to in the following sections. These procedures are summarized in Table 3 and described in Appendix B.

Figure 5. Additional Forms for Input of Corrosion Data

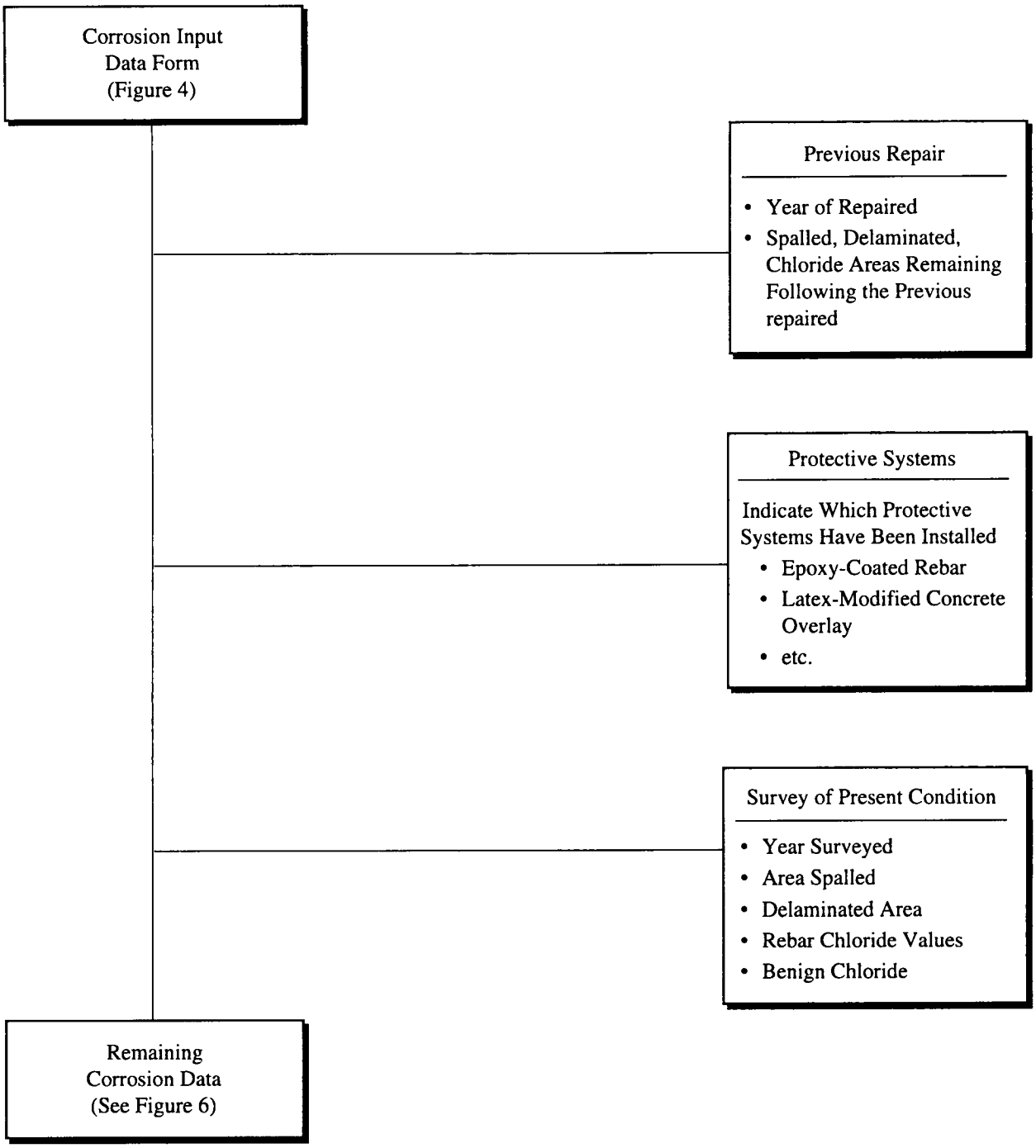


Table 3. Number of Tests and Samples

Procedure	Methodology
Visual Examination	Use 5-foot grid on deck (2.5-foot grid on sub- and superstructure) to locate defects.
Delamination Survey	Use 5-foot grid on deck (2.5-foot grid on sub- and superstructure) to locate all areas of delamination. Distinguish between delaminations and spalls.
Cover Depth	The greater of (1) 40 locations per member or (2) N=40(A/5000) locations per member, where A= area in square feet of member.
Chloride Profiles	The greater of (1) 10 locations per member or (2) N=10 (A/5000) locations per member, where A= area in square feet of member.
Corrosion Potential	Use 5-foot grid on deck (2.5-foot grid on sub- and superstructure). Additional measurements required to locate sites of anodic (highest) potential.
Corrosion Rate	Measurements at sites of anodic corrosion potentials; limited to the greater of (1) 10 locations per member or (2) N=10(A/5000) locations per member, where A = area in square feet of member.
Concrete Permeability/Resistivity	The greater of (1) 2 locations per member or (2) N=2(A/5000) locations per member, where A= area in square feet of member.

- One foot is 0.305 meter
- One square foot is 0.093 square meter

Previous Repair

When this input form is displayed, enter the following data:

- **Year of repair:** the calendar year in which the previous repair was performed.

- **Spalled, delaminated, chloride areas remaining:** three separate inputs identifying the estimated areas of spalling, delamination, and chloride-contaminated areas, respectively, that are estimated to remain following the last repair.

- **Removal cost:** the cost, in dollars per square foot, of removing a previous repair (e.g., an existing overlay) prior to performing a new treatment. This unit cost will be multiplied by the deck area, and the result will be added to the cost of any treatment. If an existing repair need not be removed, or if removal incurs no additional cost in performing a treatment, enter zero.

When you have completed your entries on this form, exit by pressing **F10** to save your work and to move to other items on the corrosion data input form. (Pressing **Escape** will also exit the form but will return you to the "previous rehabilitation" line on the input data form, forcing you to reenter the specialized form until you exit with the F10 key.)

Protective Systems

If you indicate that a protective system is installed, CORRODE displays a list of ten systems from which to make selections. You may select more than one. Indicate your selections by pressing **Enter** or **Space Bar,** both of which operate as a toggle switch. When an item is selected, a small arrowhead pointer appears to the left of the item number on the screen display. In some cases, additional technical information is requested, as noted below. The ten systems are as follows:

1. **Epoxy-coated rebar.**

2. **Latex-modified concrete overlay.**

3. **Concrete overlay:** enter the thickness of the concrete overlay, in inches, and its water-cement ratio, as a decimal fraction. These entries may be used for low-slump dense concrete as well. After you have input these values, press **F10** to save the selection of this protective system. If you press **Escape,** CORRODE will return you to the list of protective systems, but will not have selected the concrete overlay.

4. **Full depth silica fume concrete:** enter the rapid permeability test (RPT) coulomb value of the silica fume concrete deck. Exit with **F10** to save the selection, or with **Escape** to ignore it.

5. **Silica fume concrete overlay:** enter the thickness (inches) and the water-cement ratio (decimal fraction) of the silica fume overlay. Exit with **F10** to save the selection, or with **Escape** to ignore it.

6. **Asphalt concrete (AC) overlay with waterproof membrane:** enter an estimate of the additional years' protection afforded by this protective system. Exit with **F10** to save the selection, or **Escape** to ignore it.

7. **Penetrating sealer:** enter an estimate of the additional years' protection afforded by this protective system. Exit with **F10** to save the selection, or **Escape** to ignore it.

8. **Surface protective coating:** enter an estimate of the additional years' protection afforded by this protective system. Exit with **F10** to save the selection, or **Escape** to ignore it.

9. **Corrosion inhibitor concrete:** enter an estimate of the additional years' protection afforded by this protective system. Exit with **F10** to save the selection, or **Escape** to ignore it.

10. **Other systems:** enter an estimate of the additional years' protection afforded by this protective system. Exit with **F10** to save the selection, or **Escape** to ignore it.

After you have selected all applicable protective systems, save the list by pressing **F10** and return to the corrosion input data form. Pressing **Escape** will also exit the protective systems list but will cause CORRODE to ignore any of your most recent changes.

Survey of Present Condition

Data from a recent condition survey helps to establish the current condition of the bridge deck and its state of corrosion. CORRODE requires that data from a survey be input as part of the corrosion analysis. The data are as follows:

- **Year surveyed:** the calendar year in which the survey was performed.

- **Area spalled:** the area of the deck exhibiting spalling, in square feet.

- **Delaminated area:** the area of the deck exhibiting delamination, in square feet. **Note:** this area should not include any of the spalled area input above.

- **Number of rebar chloride values:** enter the number of chloride samples taken at the level of the reinforcing steel. After you enter this number and press **Enter,** CORRODE displays an input sheet in which you enter each chloride sample value, in percent of total chlorides by weight of concrete. A minimum of 10 rebar level chlorides per 5,000 square feet of deck surface exposed to salty environment (whichever is greater) is recommended. CORRODE will use this information to compute the mean and standard deviation of the chloride distribution and the estimated rebar level chloride at the 90 percent confidence limit. When you are finished entering the data, press **F10.**

- **Locked in the aggregate:** if the information and data available point to chloride-bearing aggregates in the concrete that contribute to corrosion, enter **Y**; otherwise enter **N.** If you have entered Y, CORRODE prompts you for input in the next item of the form, benign chloride.

- **Benign chloride:** if CORRODE makes this field available, enter the estimated percentage of "benign" chloride (by weight of concrete). Benign chloride refers to chloride locked in the aggregate that will not contribute to corrosion. If previous experience with the aggregate indicates benign chloride, enter the percentage here to modify the threshold chloride value used in the corrosion analysis.

When you have completed data entry to this input form, press **F10** to save these changes or **Escape** to ignore them.

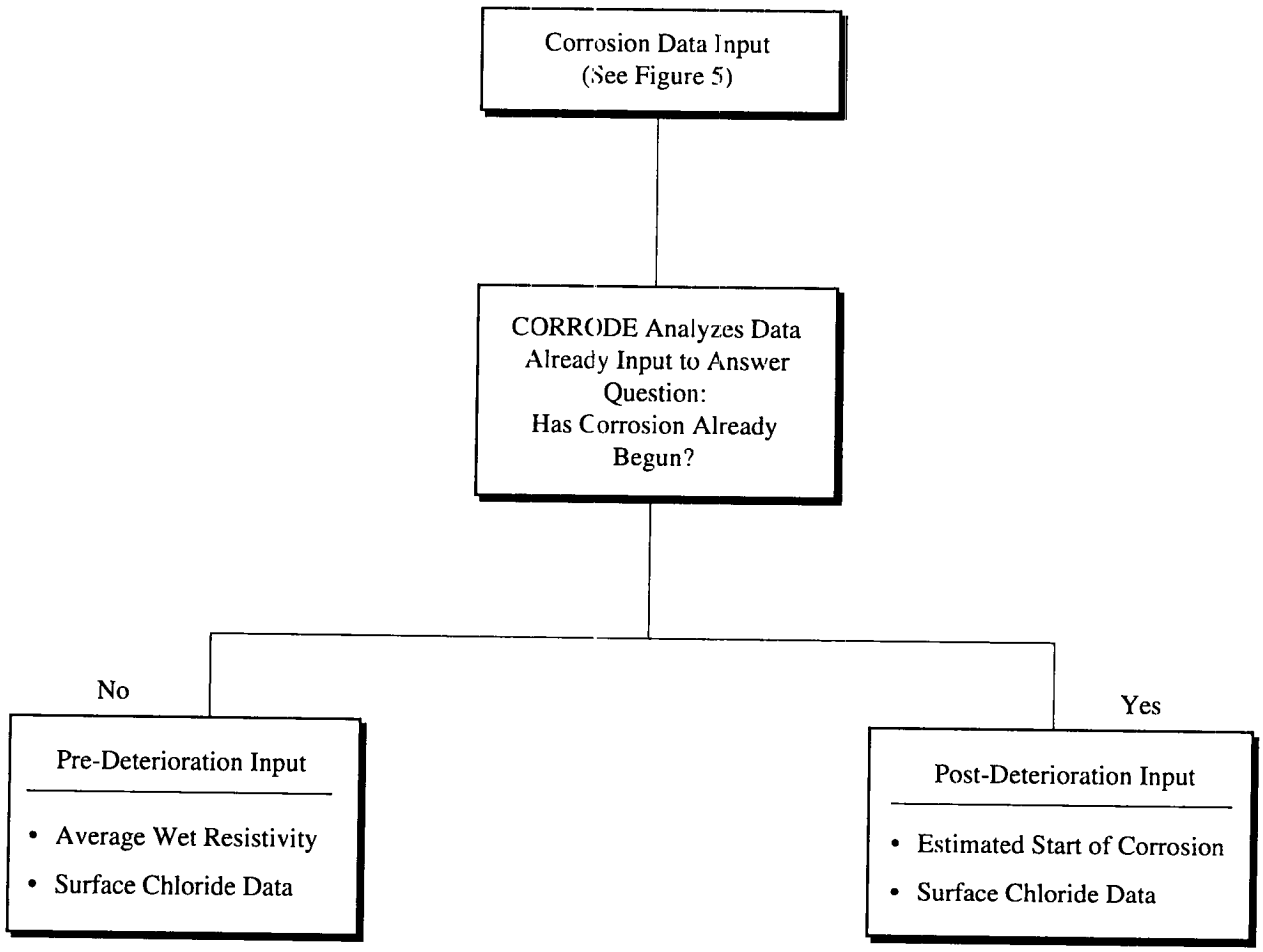
Analysis: Prior to Start of Deterioration

CORRODE's analysis of the current bridge condition may indicate that corrosion-related distress may not yet have begun. CORRODE must still estimate the slope of the deterioration versus time curve that will occur after corrosion becomes active in the future. At this future time, chloride will be present in excess at the level of reinforcing steel: the corrosion and deterioration rates will be dictated by many factors, including the steel concentration, oxygen availability, and resistivity of the concrete in the field. If CORRODE requires the information needed to estimate the rate of corrosion distress in the future, it will display a data input form entitled "Pre-Deterioration," as illustrated in Figure 6. (If this form is not displayed, you may skip this section.)

Average Wet Resistivity

The factors that will affect future corrosion cannot be known completely. However, an estimate of whether the deterioration rate will be low, medium, or high should be possible, and standard curves can be assigned to each rate designation. This estimate can be based on the wet resistivity input as follows:

Figure 6. Remaining Corrosion Data



- **Average wet resistivity:** enter the average wet resistivity of the concrete, in ohm-cm. See Appendix B for the method to determine wet resistivity.

CORRODE translates this resistivity into a rate of deterioration as follows: less than 7,500 ohm-cm, high; between 7,500 and 30,000 ohm-cm, medium; and greater than 30,000 ohm-cm is a low rate of deterioration. These results are then translated into the estimated time to reach the maximum level of distress, defining a point needed to estimate the deck deterioration function.

Surface Chloride

Surface chloride levels are part of CORRODE's estimation of future corrosion and deterioration. Data to be input are as follows:

- **Year of surface chloride survey:** enter the calendar year in which this survey was performed.

- **Number of surface chloride values:** enter the number of surface chloride values obtained in the field. After you enter this number and press **Enter,** CORRODE displays an input sheet in which you enter each surface chloride data point, in percent by weight of concrete. CORRODE will use this information to compute the mean and standard deviation of the surface chloride distribution and the estimated value at the 90 percent confidence limit. When you have finished entering the surface chloride data, press **F10.**

- **Mean annual snowfall:** enter the mean annual snowfall, in inches. This measure is used as a surrogate for salt applications on the bridge deck. It is applied only if CORRODE determines that the current surface chloride values are extremely low (average less than 0.1 percent by weight of concrete) because of lack of exposure age and that the estimate of the future time to deterioration (t_d) may therefore be incorrect. In that case, the annual snowfall will be used (with other factors) to adjust the estimated value of time to deterioration.

- **Exposed to a marine environment:** indicate (Y or N) whether the deck is exposed to a marine environment. If your response is Y, CORRODE asks you further whether the deck is within 25 feet of seawater, to which you again respond either Y or N. If your first response (on exposure to seawater) was N, then the second question is suppressed by CORRODE. These inputs are applied only if CORRODE determines that the current surface chloride values are extremely low (average less than 0.1 percent by weight of concrete) because of lack of exposure age, and that the estimate of the future time to deterioration (t_d) may therefore be incorrect. In that

case, the degree of exposure to seawater will be used (with other factors) to adjust the estimated value of time to deterioration.

Analysis: After the Onset of Corrosion

CORRODE's analysis of the current bridge condition may indicate that corrosion-related distress may have already begun. To estimate the slope of the deterioration versus time curve, CORRODE must have some information about when corrosion-related distress began. If this information is needed, CORRODE will display a data input form entitled "Post-Deterioration," as illustrated in Figure 6. (If this form is not displayed, you may skip this section.)

Two options are provided to input data on past corrosion, depending on whether you already know the year in which corrosion-related distress first occurred:

- **Know when corrosion damage started:** enter **Y** or **N**, depending on whether you know the year in which corrosion-related distress first occurred. Based on your response, CORRODE will prompt you for information in certain other fields on the form but suppress the others.

- **If so, in what year:** if your response above was yes (**Y**), enter the year in which this distress was first noticed. This year will define the estimated time to deterioration, t_d, of the bridge deck.
- **Year of surface chloride survey:** if your response above was no (**N**), data on the surface chloride level are required to estimate the time to deterioration of this deck. Enter the year this survey was made.

- **Number of surface chloride values:** enter the number of surface chloride values obtained in the survey. At least eight surface chloride levels (0.25 to 0.75 inch depth) should be determined per deck or per 5,000 square feet, whichever results in the larger number. **(These samples should not be taken in patched areas.)** After you enter this number, CORRODE displays an input sheet in which you enter each surface chloride value, as a percent. CORRODE will use this information to compute the mean and standard deviation of the surface chloride distribution and the estimated thickness at the 90 percent confidence limit. When you have finished entering the surface chloride data, press **F10**.

Corrosion Analysis Results

When all corrosion data have been entered, CORRODE will perform the corrosion analysis automatically. (**Note:** If you think all corrosion data have been entered, but the analysis has not started, try pressing **F10**. Either the analysis should begin, or

CORRODE will display another corrosion menu or input form for you to complete [e.g., the pre-deterioration or post-deterioration form].)

Distress Index, S

Note: the following brief description helps to explain the results of the corrosion analysis. A more complete discussion of the distress index, the corrosion analysis, and the resulting deterioration function to predict distress over time is given in Part I of this document.

The corrosion analysis results are expressed in terms of a distress index, denoted by S. The distress index is a composite index, a weighted average of several individual components of distress at a given time:

- **Percent of rebar level chloride contamination:** the percent of deck area in which the rebar level chloride contamination exceeds a threshold value of 0.035 percent of the weight of concrete.

- **Percent delamination:** the percent of deck area that is delaminated, excluding spalled areas.

- **Percent spalled:** the percent of deck area that is spalled.

The weighted averaging formula for the distress index at any time t is as follows:

$$S = (CL + 2.5\,DELAM + 7.5\,SPALL) / 8.5, \text{ for any time } t \qquad \text{(Eq. 5.1)}$$

where

S = the distress index, expressed as the weighted average percent of deck area that is distressed; and

CL = the percentage of deck area that is chloride contaminated

DELAM = the percentage of deck area that is delaminated

SPALL = the percentage of deck area that is spalled

The distress index is defined on a scale of 0 to 100, with an increasing index value denoting increasing distress in the deck. Although the maximum index value is mathematically 100, it is believed that a practical limit exists, beyond which a functioning deck should not go without rehabilitation. You input a value for this practical maximum level of distress.

The corrosion analysis seeks the time variation in the distress index: i.e., a deterioration function, expressed as a logistic or S-shaped curve. To estimate this curve, the corrosion analysis determines the condition of the deck at key points in its history or future, depending on whether or not the corrosion mechanisms have already begun. These key points are t_d, the time to the start of deterioration; t_p, the present time; and t_m the time to reach the maximum level. To estimate the deterioration function, the corrosion analysis requires that only two of these three points be determined.

It is assumed that at the time to the start of deterioration, t_d, the condition index is defined to have a value of 1.9. This value corresponds to the assumption of 10 percent chloride contamination, 0 percent delamination, and 0 percent spalling. Thus, the corrosion analysis needs only to determine t_d to obtain one of the two required points. It computes t_d using a modified Stratfull formula.

For the second point, the corrosion analysis uses one of the following two approaches, depending on whether corrosion has already begun or will begin in the future:

- **The current deck condition:** Since the present time is known, this procedure determines the present level of distress S_p from technical information and the results of field surveys that you input in the corrosion menu.

- **The limiting deck condition:** This procedure determines the time at which the deck will reach the practical maximum level of distress, estimated from the technical data you input in the corrosion menu.

Display of Corrosion Results

Results of the completed corrosion analysis are displayed in a special screen containing the following information:

- **Year of construction:** the year of deck construction or replacement that you entered in BRIDGES.

- **Key points in the distress versus time curve:** distress index values at two of the three possible points are given. These values are based on the present condition of the deck if corrosion has already begun, or upon the predicted future trend of corrosion and related distress if the corrosion mechanism has yet to manifest itself. The possible points are (1) the time to deterioration, t_d; (2) the present time, t_p; and (3) the time to reach the maximum distress, t_m.

- **Deterioration function:** expressed as an S-shaped curve of the following form: $S_t = 100 / (1 + A \exp(-Bt))$. This curve is derived from fitting a logistic function to two of the three points discussed above.

- **Time to deterioration:** the effective value of t_d, in years, based on the corrosion data you have provided.

The life-cycle cost analysis discussed in the next section requires a deck deterioration function estimated by the corrosion analysis. If you wish to save the deterioration function displayed on the results screen for possible future use, press **F10** after you have reviewed all of the information on the screen. Press **Escape** to return to the corrosion analysis.

5.3 Life-Cycle Cost Analysis

Note: the life-cycle cost analysis always applies to the "selected" bridge, i.e., the bridge whose file name is identified in the information bar at the bottom of the screen. If the bridge you wish to study is not currently selected, go to the BRIDGES option and select the desired bridge before proceeding with the life-cycle cost analysis. (Refer to Chapter 3 for how to select a bridge.)

Life-Cycle Analysis File Selection

Once you have entered the life-cycle cost submenu, CORRODE prompts you for the following information:

- **Corrosion analysis file:** select the name of the corrosion analysis file to be included in the life-cycle cost analysis. This file selection determines the specific deterioration model to be applied to predict deck distress over time. Press **Enter** when finished.

- **Treatment definition file:** select the name of the treatment file to be included in the life-cycle cost analysis. This file selection determines the specific treatment to be applied, for which the optimal time and cost will be determined. Press **Enter** when finished.

- **Discounting rate:** enter the discount rate, in percent, to be used in the analysis. Your agency may have already established the value of discount rate to be used in economic analyses of project alternatives. The discount rate at the federal level is set by the Office of Management and Budget. If no information on discount rate is available, use the guidance in the AASHTO "Red Book."[10]

- **Results file:** the results of the current life-cycle cost analysis will be stored in the file you identify here. Choose a name that conforms to DOS naming conventions. If the name you enter matches that of a previously defined life-cycle cost file, CORRODE will ask you, **"OK to overwrite existing file?"** If you respond no (N), CORRODE will return you to the

entry field so that you may modify the name you had entered. If you respond yes (**Y**), CORRODE will proceed with the analysis — all previous contents in the results file will be lost.

Life-Cycle Analysis Results

When you have completed data input, press **F10**. CORRODE will automatically begin the life-cycle cost analysis. When the analysis is completed, CORRODE will display a screen entitled, "Life-Cycle Cost Analysis Solution." This screen gives the optimal time to perform the treatment you had selected earlier for the bridge and the associated corrosion model that you also selected.

A message informs you that reports and graphs can be obtained for this solution, specifying the file name that you should use to obtain these results. The file name is the same as the "results file" name you specified earlier in the life-cycle analysis menu. When you have finished reading this screen, press any key to return to the CORRODE life-cycle cost submenu.

If the life-cycle cost analysis detects inconsistencies in the bridge, corrosion, and treatment data that have been specified, it will display a message to that effect. For example, if you have input a preventive treatment, but the corrosion analysis shows that corrosion has already started, CORRODE will display a message pointing to this contradiction and suggesting that you either check the corrosion data or describe a corrective rather than a preventive treatment.

6. Viewing Results

6.1 Overview

CORRODE provides several ways to view your results of the corrosion and life-cycle cost analyses. Several types of reports and graphs are provided, as described in the following sections. These displays and features are available in the REPORTS and the GRAPHS options of the main menu bar, respectively, as shown in Figure 7.

Note: reports and graphs are available only for the selected bridge: i.e., the bridge whose file name is displayed in the information bar at the bottom of the screen. If you desire reports for a bridge other than the one displayed, return to the BRIDGES option to select a new bridge before proceeding with REPORTS or GRAPHS. (Refer to Chapter 3 for selecting bridge file names.)

6.2 Reports

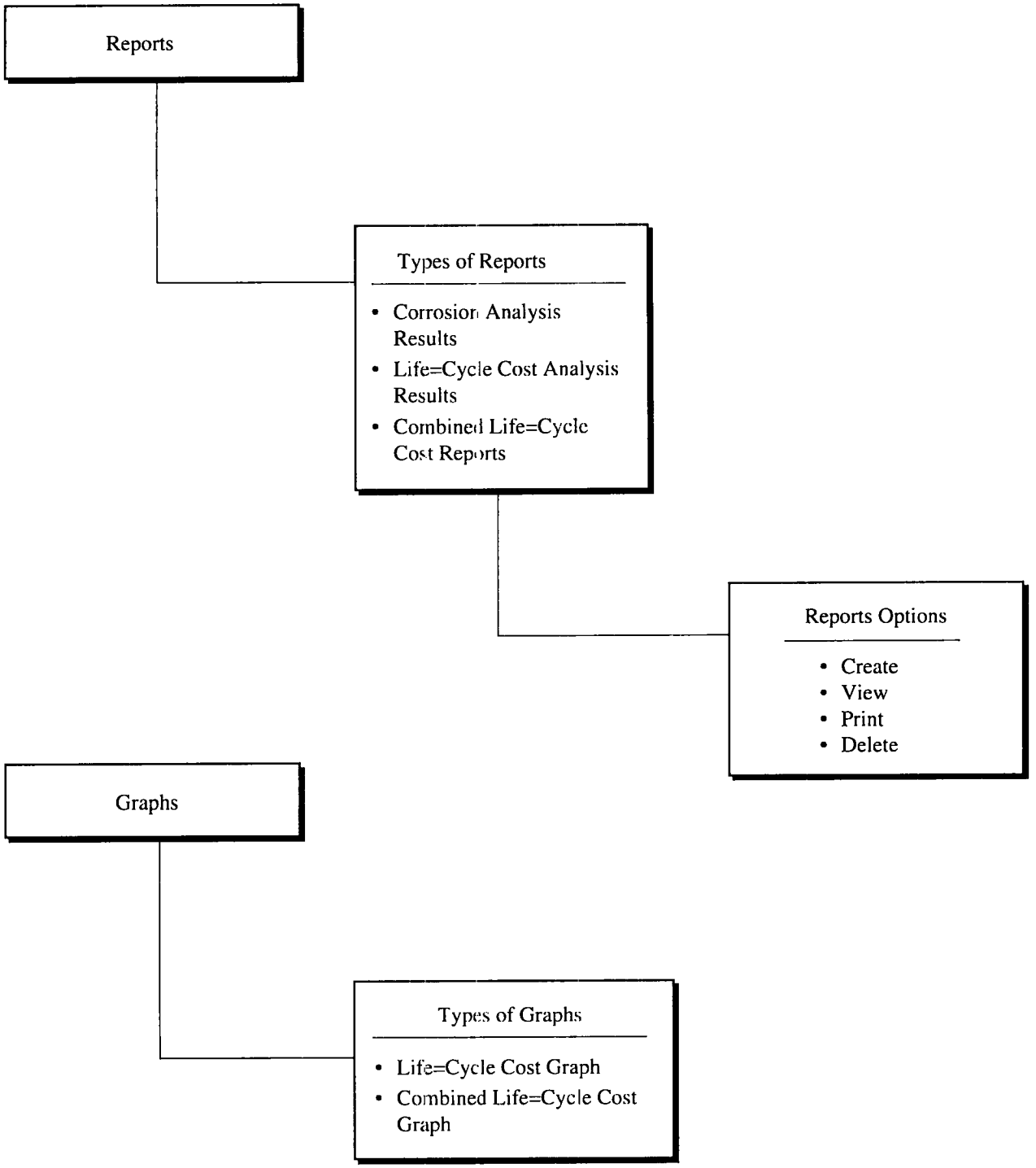
Types of Reports

CORRODE provides you several choices in the REPORTS submenu:

- **Corrosion analysis results:** a summary of the key data that you have entered and the results of the corrosion analysis. The information displayed includes the bridge file name, any comment you may have entered in BRIDGES, general bridge characteristics, results of the survey of deck distress, rebar chloride values, the current value of the distress index S_p, estimated points of the deck's distress history, the estimated time to deterioration t_d, and the estimated deterioration function S_t.

- **Life-cycle cost analysis results:** a tabulation of the results of a single life-cycle cost analysis for each year, showing the computed agency cost, user cost, and total cost (in thousands of dollars), and identifying the optimal treatment time (i.e., the year with the lowest life-cycle cost). These results apply to a single bridge (the selected bridge) and one treatment; the results that are displayed are retrieved from a single life-cycle cost file.

Figure 7. Viewing Results



- **Combined life-cycle cost reports:** a comparison of the life-cycle cost results of several analyses. This report tabulates for each year the computed total cost (in thousands of dollars) for up to six life-cycle cost analyses. The optimal treatment time is identified by an asterisk for each case. These results apply to a single bridge (the selected bridge) and to multiple treatments or variations in treatments, depending on the structure of your analyses. The results that are displayed are retrieved from multiple life-cycle cost files. Refer to the next section to learn how to choose which results will be displayed.

Report Options

When you choose one of the three reports above, CORRODE then displays a second submenu from which you select the action you would like to perform. For each type of report CORRODE provides the following capabilities:

- **Create:** generates a report from a file for the first time. CORRODE prompts you for two file names: (1) the name of the file containing the data to be displayed (select from the list CORRODE provides you); and (2) the name of the file in which the report itself will be stored (enter this name in the field provided. This name is limited to eight characters and must conform to DOS-naming conventions.)

- **View:** displays a report on the screen in tabular form. Select one of the report file names listed by CORRODE. If no reports have been defined yet for the selected bridge, CORRODE will display a message to this effect.

- **Print:** sends a report file to the printer. CORRODE prompts you for two responses: (1) the name of the report file to be printed (select one from the list CORRODE provides you); and (2) printer instructions. You must select a name of the report file from the list presented. The second field may be left blank.

  The CORRODE installation procedure loads the SETUP.PRN file with commands for an Epson-compatible printer. This set of commands works reliably with many printers. If you have printer formatting problems when trying to print reports, try the following:

  1. Verify that a file SETUP.PRN exists in the CORRODE subdirectory. If not, create an empty file of this name, and try printing again.

2. Copy the current contents of SETUP.PRN to a dummy file; then, erase the contents of SETUP.PRN so it is an empty file. (Essentially, you will be invoking your printer's default options.)

3. If the first or second step does not solve the problem, enter an escape command in SETUP.PRN that is appropriate to your printer. Consult your printer manual for the series of commands required.

These suggestions are intended only for problems in formatting printed reports. If none of these steps solves the problem, review the system messages you are receiving to determine whether other causes besides printer communications are preventing you from obtaining a report: e.g., failure to define a reports file; a different user id or selected bridge from that used to create a reports file originally; or inadvertent deletion of a reports file.

- **Delete:** erases a file.

All of the commands above work in a similar way:

- When you must select a file name from a list of previously defined files, CORRODE will always present the correct list of files to you. For example, if you are creating a corrosion report, CORRODE will identify the list of valid corrosion files. For creating the two life-cycle cost reports, CORRODE will display the valid life-cycle cost files.

- The combined life-cycle cost report allows you to select a range of files to be included in a report: a minimum of one file, to a maximum of six. All valid life-cycle cost files will be displayed for your selection. If you wish to display fewer than six files, select **none** for the remaining slots.

- The displayed list of files will always pertain to the selected bridge **and** the current user id (the three initials entered in the title screen — see Chapter 2). If you do not find the file name you are looking for, check to see that (1) you are currently logged in under the same user id that was used when the file was created and (2) the currently selected bridge is the same as that for which the file was created.

- When you are presented with a list, press **Enter** to select a name from the list; press **F10** to complete and execute the command, or press **Escape** to cancel the command and return to the REPORTS submenu.

6.3 Graphs

CORRODE displays graphs of life-cycle cost results on the screen. These graphs help you visualize a solution and gauge the sensitivity of the life-cycle costs of a treatment to the timing of its application. They also provide a quick way to compare different life-cycle treatments in terms of their costs versus time. The options presented in the submenu correspond to the two types of graphs available:

- **Life-cycle cost graph:** a graphic display of the life-cycle cost report for a single treatment discussed in the preceding section. The graph displays three cost curves against time in years: agency costs, user costs, and total costs. The optimal solution occurs at the point of minimum total cost.

- **Combined life-cycle cost graph:** a graphic display of the combined life-cycle cost report discussed in the preceding section. The graph displays curves of total costs versus time in years for up to six different life-cycle cost analyses. This graph is useful to compare different alternatives regarding treatments.

Working with graphs follows the same conventions as discussed for the life-cycle cost analyses and reports, since reports and graphs are derived from the same life-cycle analysis results files:

- CORRODE will automatically present the valid list of life-cycle cost files from which you may select those to appear in a graph.

- The combined life-cycle cost graph allows you to select a range of files: a minimum of one file, to a maximum of six. All valid life-cycle cost files will be displayed for your selection. If you wish to display fewer than six files, select **none** for the remaining slots.

- The displayed list of files will always pertain to the selected bridge **and** the current user id (the three initials entered in the title screen — see Chapter 2). If you do not find the file name you are looking for, check to see that (1) you are currently logged in under the same user id that was used when the file was created and (2) the currently selected bridge is the same as that for which the file was created.

- When you are presented with a list, press **Enter** to select a name from the list; press **F10** to complete and execute the command, or press **Escape** to cancel the command and return to the GRAPHS submenu.

There are no file management commands (such as file deletion) associated with GRAPHS, since no permanent files are created. The graphs are generated for screen display each time they are needed.

7. File Management

7.1 Overview

CORRODE maintains a system of directories and files to help it do its work. Necessary subdirectories are created during the installation procedure, all located within the CORRODE directory. While these subdirectories and the files therein all follow DOS conventions, you should not attempt to use DOS to work with them. Many of these files contain not only your data and results but also information that helps CORRODE locate files and link information among files. By attempting to access these files through DOS, you may inadvertently change them or delete them in ways that will disable them for use by CORRODE. Messages to the effect that "files are not available" may result if these files are corrupted. (See also the section below, on user id and path conventions.)

All management of files should be done through CORRODE's command structure. Previous chapters have already introduced you to several of CORRODE's file management commands: e.g., creating and editing bridge and treatment files in Chapters 3 and 4 (as well as copying treatment files in Chapter 4), the creating of analysis files in Chapter 5, and creating and deleting report files in Chapter 6. In this chapter, the remaining file management option will be introduced, the overall DELETE command. DELETE is the last option on the main menu bar at the top of the screen.

7.2 The DELETE Option

The DELETE submenu lists four types of files:

- **Bridge files:** select this option to delete files created in BRIDGES.
- **Corrosion files:** select this option to delete corrosion files created in ANALYSES.
- **Treatment files:** select this option to delete files created in TREATMENTS.
- **Life-cycle files:** select this option to delete life-cycle cost files created in ANALYSES.

These submenu options all operate in a similar way:

- Choose the type of file to delete by pressing **Enter**. CORRODE will list the names of currently existing files for the selected bridge that bear your id (i.e., that are identified by your initials as entered on the title screen).

- To select the name of the file to be deleted, move the cursor to the appropriate name and press **Enter**. CORRODE will prompt you with a message confirming that you indeed wish to delete the file. Select **Y** to proceed with the deletion, or **N** to quit the operation.

Note: Before deleting a bridge file, **please confirm that the bridge is not the "selected" bridge identified in the information bar at the bottom of the screen.** Select another bridge (using the "Select" command described in Chapter 3) before deleting the bridge file in question.

Appendix A

Input Data Defaults and Example Values

Table A.1. Bridge Input Data

Item	Default	Example
Bridge Name	Default	Example
Comment	No Comment	An example of bridge input data--for illustration only
Year (re)constructed	1965	1965
Deck area, sq ft	100	4,000
Traffic, veh/day	100	40,000
Normal capacity, veh/day	100,000	96,000
Average crossing time, minutes	1	0.02841
User cost coefficient, $/veh	0	0.00710
User cost exponent	4.0000	4.0000

Table A.2. Treatment Input Data

Item	Default	Example
Treatment Name	Default	Example
Comment	No Comment	An example of treatment input data--for illustration only
Costs and productivity	Y	Y
Estimated life and repair	Y	Y
Effect on traffic	Y	Y
Adjustment factors	N	Y

Table A.3. Treatments: Costs and Productivity Data

Item	Default	Example
Fixed cost, $	0	10,000
..time required, days	0	5
Deck cost, $/sq ft	0.00	6.00
..productivity, sq ft/day	0.00	400.00
CL cost, $/sq ft	0.00	0.00
..productivity, sq ft/day	0.00	0.00
DL cost, $/sq ft	0.00	0.00
..productivity, sq ft/day	0.00	0.00
SP cost, $/sq ft	0.00	35.00
..productivity, sq ft/day	0.00	135.00
Maintenance cost, $/year	0	0

Table A.4. Treatments: Estimated Life and Repair (After-Treatment Data)

Item	Default	Example
Effect on chloride	N	Y
CL following treatment, % of area	0.0	0.0
Effect on delamination	N	Y
DL following treatment, % of area	0.0	0.0
Effect on spalls	N	Y
SP following treatment, % of area	0.0	0.0
Nominal life, years	0.0	10.0
Corrosion model	1	3
K	0.3333	0.0000
Life with no corrosion, years	0.0	--

Table A.5. Treatments: Effect on Traffic

Item	Default	Example
Traffic Impact	Congestion	Congestion
Unit user cost, $/min per veh	0.0000	0.25
Congestion formula coefficient	0.1500	0.1500
Congestion formula exponent	4.0000	4.0000
Capacity during project, veh/day	100,000	100,000
Detour time, min/veh	0.00000	--

Table A.6. Corrosion Input Data

Item	Default	Example
Analysis base year	1994	1994
Maximum tolerable distress	45.0	45.0
Previous repair	N	N
W/C deck concrete	0.50	0.45
Number of cover data	1*	10*
Protective system	N	N
Present condition	Y*	Y*

*Example data for illustrative purposes only are provided in input forms invoked by these selections.

Table A.7. Corrosion: Previous Repair Data

Item	Default	Example
Year of repair	1975	
Spalled area remaining, sq ft	0	
Delaminated area remaining, sq ft	0	
Chloride area remaining, sq ft	0	
Removal cost, $/sq ft	0	

Note: data in this menu not required for the example provided.

Table A.8. Corrosion: Present Condition Information

Item	Default	Example
Year surveyed	1993	1993
Area spalled, sq ft	0	0
Delaminated area, sq ft	0	0
Number of rebar chloride values	1*	10*
Locked in the aggregate	N	N
Benign chloride, % by weight of concrete	0.00000	--

*Example data for illustrative purposes only are provided in input forms invoked by this selection.

Table A.9. Corrosion: Pre-Deterioration Data

Item	Default	Example
Average wet resistivity, ohm-cm	1000	500
Year of surface chloride survey	1993	1993
Number of surface chloride values	1*	10*
Mean annual snowfall, inches	0	20
Marine environment	N	N
Within 25 ft of seawater	N	--

*Example data for illustrative purposes only are provided in input forms invoked by this selection.

Table A.10. Corrosion: Post-Deterioration Data

Item	Default	Example
Know when corrosion damage started	N	
If so, in what year	1975	
Year of surface chloride survey	1993	
Number of surface chloride values	1*	

*Example data for illustrative purposes only are provided in input form invoked by this selection.

Note: data in this menu not required for the example provided.

Appendix B

Descriptions of Tests

APPENDIX B

Descriptions of Tests

B.1 Visual Examination

A visual examination of the concrete surface is used to determine the extent of deterioration and forms the basis for the subsequent concrete condition surveys. The visual examination described here is not related to the biennial bridge survey adopted by the Federal Highway Administration. The visual examination notes both corrosion and non-corrosion-related deterioration. It should note size, location, and orientation of

1. Spalls
2. Patches (temporary and permanent)
3. Scaling
4. Pop-outs
5. Cracks
6. Wheeltrack wear

These items should be shown on a sketch. A grid layout is established on the concrete surface to map concrete deficiencies and to determine their **magnitude** based on a percent of surface area. The **severity** of the deterioration should be determined quantitatively during a visual examination by measuring the depth of spalls, scaling, and wheeltrack wear. Exposed and corroding reinforcing steel should also be noted.

The visual examination generates a comprehensive condition survey of the concrete surface. It determines the extent of corrosion-induced spalling as well as the significance of deterioration caused by reasons other than corrosion of the reinforcing steel. The output of this procedure for use in the calculations is the percent of the area which has spalls, temporary patches covering spalls (e.g., asphalt patches), and permanent patches (e.g., concrete patches).

This methodology cannot be used to determine remedial actions for non-corrosion-related deterioration (e.g., scaling, pop-outs, surface cracking, and wheeltrack wear). If non-corrosion-related deterioration is significant, the most cost-effective treatment may be obtained by considering factors which are not covered in this methodology.

B.2 Delamination Survey (ASTM D4580)

This test (ASTM D4580) is used to survey concrete by sounding the surface to determine the presence of delaminations (corrosion-induced internal cracks). To conduct this test, first a grid layout is established on the concrete surface. Second, the surface is sounded and delaminations noted. Third, the areas of delamination are marked and mapped for the report. Fourth, the amount of delamination is computed as a percentage of the surface area. Spalls **are not** included.

Where rigid overlays are applied, ASTM D4580 shall distinguish delaminations from debonding of the overlay. Where asphalt concrete overlays are applied, delaminations and/or debonding should be detected using the procedure recommended by Strategic Highway Research Program, "Method for Evaluating the Condition of Asphalt-Covered Bridge Decks." The SHRP test method is documented in Appendix B of SHRP research by Cady and Gannon.[3]

If overlay debonding is significant, the most cost-effective treatment may be obtained considering factors which are not covered in this methodology.

B.3 Cover Depth over Reinforcement Using a Cover Meter (Magnetic Flux Device)

This device uses a magnetic field to detect reinforcing steel within hardened concrete. It can determine the location, orientation, size, and depth of the bar. The accuracy of the device in measuring the depth of cover decreases as the depth of cover increases. Magnetic particles in the concrete can influence the measurements. Thus, a correction factor should be obtained by exposing the bar at one location and measuring the actual depth. Usually, the correction factor is obtained at a location which can later serve as the half cell test bar ground connection.

If the bar size is not known, the depth cannot be read directly from the scale; therefore, the following technique is suggested.

1. Locate the bar in the test area.

2. Place a two-by-four or other non-metallic spacer between the probe and the concrete surface.

3. Record possible bar size and depth combinations.

4. Correct readings for the thickness of the spacer by subtracting its thickness.

5. Place the probe directly on the concrete surface and record possible reading.

The bar size for which the same cover depth is obtained in steps four and five is the correct result.

B.4 Reinforcing Steel Electrical Continuity

Electrical continuity of the reinforcing steel should be known prior to conducting certain tests or applying certain treatments. Electrical continuity can be determined by measuring the resistance between widely separated steel components. Low resistivities indicate continuity.

B.5 Chloride Profiles (AASHTO T260-84, or SHRP Modified Test Method)

This test determines the chloride content of concrete. Concrete powdered samples are collected with a vacuum bit near the concrete surface (0.25 to 0.75 inch depth) and at the level of the reinforcing steel (the bottom 0.25 inch of concrete cover). Where a concrete overlay is applied, "concrete surface" is the surface of the overlay.

The SHRP "Test Method for Field Determination of Total Chloride Content is documented in Appendix F of Cady and Gannon.[3] In the SHRP test method, which is a field method, the powdered samples are dissolved in, and stabilized by, two solutions. A probe is then inserted into the mixture and the readings are recorded in the field. Calculations convert readings into chloride content expressed as a percentage of concrete weight.

AASHTO T260-84 test method may also be used for chloride content determination.

B.6 Corrosion Potential Survey (ASTM C876)

This procedure (ASTM C876) determines the potential for the existence of reinforcing steel corrosion by measuring the electrical potential of the reinforcing steel. It may be performed if 10 percent of the chloride samples at the depth of the steel are greater than the corrosion threshold chloride content.

The procedure for administering this test follows:

1. Establish a grid on the concrete surface.

2. Provide an electrical connection to the steel (ground).

3. Place a half cell corrosion detection device on the concrete surface at the grid points.

4. Record the electrical potential readings.

Note that the test cannot be conducted in the absence of the electrical continuity of the reinforcing steel.

This procedure obtains the location of highest half cell potentials (peak negative potentials) for the subsequent rate of corrosion testing. The location of highest potentials can be obtained in the field by scanning the concrete surface around the anodic areas with a half cell device. The locations of anodic areas are obtained by plotting the grid half cell potentials and drawing equipotential contour lines.

The corrosion potential survey is not recommended for epoxy-coated or galvanized reinforcement. This is because epoxy-coated bars are electrically insulated from each other, and readings on galvanized bars indicate the potential of the zinc coating. Also, the test cannot be conducted where concrete is overlaid with a dielectric material, such as a membrane, polymer material, or asphalt, unless the asphalt is saturated.

B.7 Rate of Corrosion Measurement

The SHRP Standard Test Method for Measuring Instantaneous Corrosion Rate of Reinforcing Steel is documented in Appendix A of Cady and Gannon.[3] The test should be conducted at locations of highest corrosion potentials (peak negative values) subsequent to the half cell test. Corrosion rate tests should not be carried out where epoxy-coated or galvanized reinforcement is used.

To conduct this test, first mark the bar location and record the bar size and depth. The presence of any lap splices should be noted at the test site. Second, establish an electrical connection to the reinforcement, and determine the corrosion potential directly over the bar of interest. Note that the electrical connection provided for the corrosion potential survey can be used for this purpose. Third, use one of the three devices listed below to take readings:

1. The 3LP device by KCC, Inc., U.S.A.

2. NSC device by Nippon Steel Corporation, Japan

3. Gecor Drive by GEOCISA, Spain

Each device determines the polarization potential of the reinforcing steel. Corrosion current is calculated from a simple equation and expressed in terms of milli-amperes per square foot of reinforcing steel area (mA per sq ft). Note that the three devices listed yield different but related results. Values obtained by any of the device may be recalculated into values of another devices by using the empirical formulas presented below:

$\log I_c$ (3LP) = 0.47 + 0.84 $\log I_c$ (NSC)
$\log I_c$ (GECOR) = -0.47 + 0.77 $\log I_c$ (NSC)
$\log I_c$ (GECOR) = -0.90 + 0.92 $\log I_c$ (3LP)

B.8 Permeability of Concrete, and Concrete Resistivity (ASSHTO T277)

This test (AASHTO T277) determines the relative permeability of the concrete (or concrete overlay). Also, the test may be modified to determine the concrete's "wet" resistivity. A suggested procedure for this purpose is described in Appendix E of Part I of this document.

Many highway agencies are currently using AASHTO T277 (Rapid Determination of the Chloride Permeability of Concrete), which requires coring concrete and conducting a laboratory test. The permeability is indicated by the electrical charge passed through the concrete. The electrical charge is expressed in terms of coulumbs, and the concrete electrical resistivity is expressed in terms of ohm-cm.

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